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Long-term Cost-effective Trunk Main Discoloration Risk Management Strategy

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Thesis submitted for the degree of Doctor of Philosophy

The University of Sheffield

Department of Civil and Structural Engineering

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Dedicated to my parents….

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Executive Summary

Material responsible for discolouration risk has been shown to accumulate on pipe walls even after cleaning intervention, suggesting that risk cannot be eliminated with a single applied intervention and hence the long-term water quality benefits are uncertain. This recurring cleaning requirement can substantially increase total expenditure on interventions. Although different interventions exist to manage accumulated material, flow conditioning is considered to be a long-term intervention due to the use of only system hydraulic (shear stress) with minimal resources. The water quality performance of the selected intervention was tested in multiple operational trunk mains including a control main with similar physical, chemical and microbiological conditions and their discolouration risk and chlorine wall decay were measured as a water quality performance indicator. The periodic trunk main flow conditioning improved the long-term chronic material loading and chlorine wall decay of trunk mains compared to the control. Although transport of occasional acute loading to the downstream network from the flow conditioning trial was recorded, the improved downstream accumulation return period found for the flow conditioned main evidenced that chronic loading has a significant influence on discolouration risk than acute loading. Using the field observed material accumulation processes for large diameter main and long-term measured data, the Variable Condition Discolouration (VCD) model was used successfully to simulate long-term discolouration behaviour with high accuracy and the model's accumulation functionality was validated. This fundamental way of capturing accumulation behaviour in the VCD model was used to develop a novel whole life costing (WLC) model for designing flow conditioning intervention cycle cost trading against hydraulic resilience. The WLC modelling framework derived exponential Pareto front solutions that can select best solutions between intervention expenditure and level of resilience achieved. This research enlightens for the first time how the trunk main and downstream network discolouration risk behaves in response to periodically controlled interventions and how risk can be managed proactively and strategically from treatment works to trunk main and downstream distribution zone.

Used Resources and Software

Most of the software are used for this thesis is available under open source license and some are commercial. The author would like to thank all those individual/companies who develop the below listed software and equipment.

Software

- Thesis writing: Microsoft Word 2010
- Discolouration modelling: Variable Condition Discolouration Model (coded in Python (x,y) v2.7.6.1), PODDS (Prediction of Discolouration in Distribution System) model (EPANET version)
- Hydraulic modelling: EPANET2 (Rossman, 2000)
- Chlorine decay modelling: EPANET2 (Rossman, 2000)
- Optimisation software: PEST (Doherty, 2005)
- Statistics analysis: IBM SPSS v22.0, Python (x,y) v2.7.6.1
- Data accumulation and organisation: MS excel 2010
- Graph, Plotting and Image drawing: Python (Matplotlib function), Plotly, Inkscape, MS Excel 2010, MS PowerPoint 2010
- PhD Project Schedule: MS Project and MS excel
- Referencing software: Zotero

Equipment

- Turbidity loggers: ATI Nephnet, Evoqua Hydraclam, Hach 2100Q Handheld, Sigrist Aquascat 2
- Chlorine logger: Evoqua Chloroclam, Hach Pocket Colorimeter II
- Flow meter: ABB Aquamaster
- Pressure logger: Syrinix Transientminder

Abbreviations

DWDS	Drinking Water Distribution System
WTW	Water Treatment Works
WDN	Water Distribution Network
WDS	Water Distribution System
DMA	District Metered Areas
DWI	Drinking Water Inspectorate
PODDS	Prediction of Discoloration Events in Distribution Systems
VCD	Variable Condition Discoloration
DRM	Discolouration Risk Model
DPM	Discolouration Propensity Model
PSM	Particle Sediment Model
ANN	Artificial neural network
EPR	Evolutionary Polynomial Regression
AMP	Asset Management Period
PRV	Pressure Reducing Valve
UDF	Unidirectional Flushing
CI	Cast Iron
DI	Ductile Iron
TSS	Total Suspended Solids
CI	Cast Iron
PE	Polyurethane
AC	Asbestos Cement
ID	Internal Diameter
IPR	Intellectual Property Rights
WLC	Whole Life Costing
CBA	Cost Benefit Analysis
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
TOTEX	Total Expenditure
GI	Gastrointestinal Illness
UF	Ultra-filtration

Symbols and Notations

Symbol	Significance	SI Unit
A	Cross-sectional area	m^2
C	Stored volume of material on the pipe wall	$NTU.m^3$
C	Particle concentration in bulk water	ppm
C_{max}	Maximum material volume for a fully developed layer	$NTU.m^3$
C_w	Particle mass in pipe wall	ppm
C_{∞}	Final steady state particle concentration	ppm
g	Acceleration due to gravity	m/s^2
h_L	Total head loss	m
k	Gradient of discolouration potential	No unit
k_s	Pipe roughness height	mm
n	exponential coefficient of force required to erode	No unit
P	Pressure	bar or m
P	Linear coefficient of force required to erode	$NTU.m^3.N^{-1}.s^{-1}$
Q	Flow	m^3/s or l/s
R	Rate of supply from unit wall area	$NTU.ms^{-1}$
R	hydraulic radius	m
Re	Reynolds no	No unit

S_0	hydraulic gradient	No unit
T	Turbidity	NTU
v	velocity	m/s
α	material release coefficient	$NTU.m.s^{-1}$
α	Decay coefficient	No unit
β_e	mobilisation rate	$N^{-1}m^{-2}s^{-1}$
β_r	accumulation rate	s^{-1}
β	Wall mass coefficient	No unit
τ	Shear stress	N/m^2
ρ	Density	kg/m^3

1. Introduction

Drinking water assets must be managed in order to provide high-quality water with adequate pressure (Alegre et al., 2010; WHO, 2011). It is essential for water suppliers to provide clean drinking water to safeguard public health and well-being. However, water quality deteriorates as it flows through drinking water networks due to a complex set of physico-chemical and microbiological processes (Tamminen et al., 2008). As a consequence, this continuous water quality deterioration in the distribution system must be managed throughout the service life of the distribution main. A key water quality issue, discolouration is the most apparent and most often reported water quality complaint around the globe. Discolouration is primarily considered an aesthetic complaint that lowers the confidence of consumers and regulators in the water supplier and hence impacts their reputation. Even after modern water treatment procedures, particles remain in bulk water along with the solute that has accumulated on the pipe wall over time. These accumulated materials can be mobilised due to the hydraulic disturbance, causing discolouration events.

The water distribution system, with its various components, is a complex network covering many miles within geographical areas. Figure 1 shows an example of water distribution network layout in a large geographical area. Due to the most of the network is being buried under soil, and network redundancy, it is a difficult task to investigate the asset deterioration and conduct any rehabilitation of the network without causing customer disruption. The water quality regulator of England and Wales, the Drinking Water Inspectorate (DWI), has reported that 37% of discolouration incidents originated from the planned maintenance work in 2014, which was lower than the 48% in 2007 (DWI, 2007, 2014). This suggests that network management techniques are improving in terms of the management of discolouration problem, but they remain unacceptable.

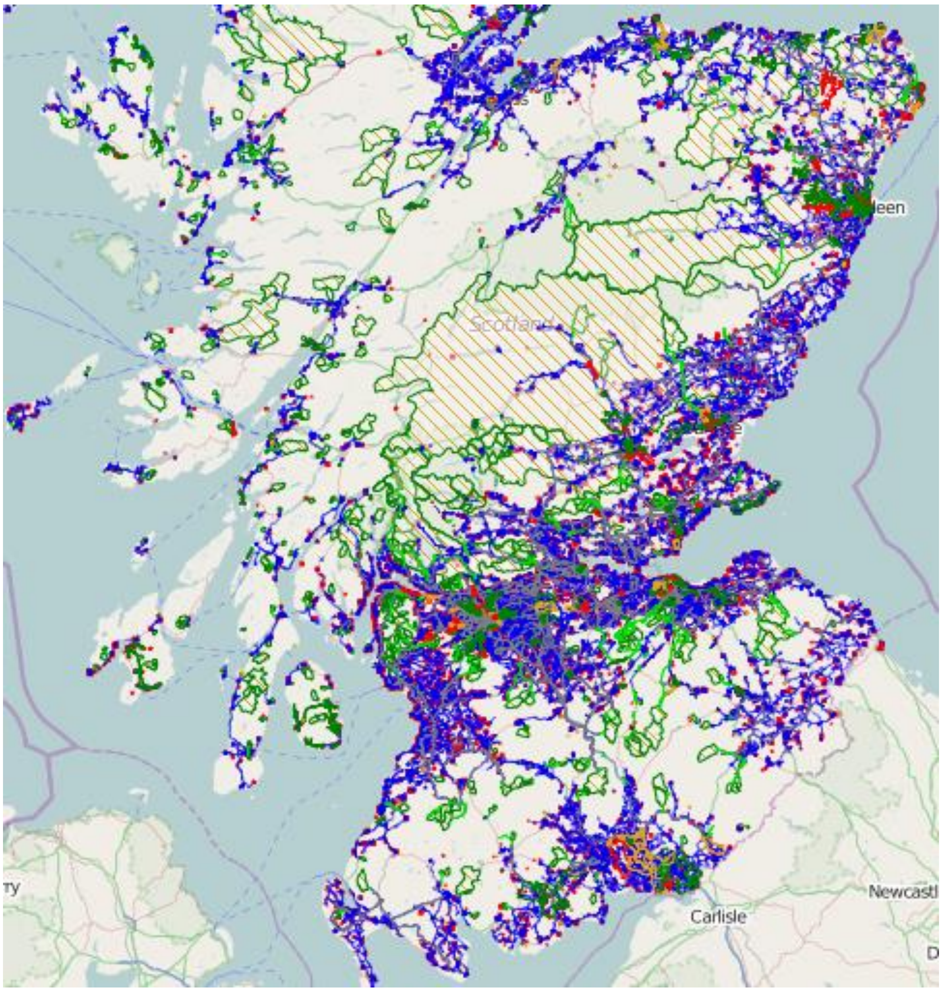

Figure 1: Geographical distribution of water distribution systems in Scotland where blue line representing the water distribution network

The water industry has traditionally removed accumulated material from drinking water pipe walls by various cleaning techniques (Ellison, 2003; Friedman et al., 2012). However, these techniques are expensive, reliant on specialist resources, and disruptive to the customer, as pipe needs to be isolated during the operation. Although short-term water quality improvement has been reported as a result of these strategies, their long-term benefit remains unknown.

Several investigations have demonstrated that, following flushing, discolouration material returns to the pipe wall (Blokker and Schaap, 2015a; Cook and Boxall, 2011; Husband et al., 2010) and water quality contacts reported even after the traditional invasive interventions (Boxall et al., 2003a), suggesting the limitations of a single intervention. The return rate of discolouration material after cleaning is largely unknown, leading to uncertainty about maintenance frequency and the cost-effectiveness of network management strategies. These uncertainties could increase the operational expenditures (OPEX) substantially compared to capital expenditures (CAPEX). Typically water companies are obligated to follow the statutory and regulatory requirements set by their government regulators, in which water utilities essentially meet regulatory requirements by being commercially viable and providing the best service at the lowest sustainable cost to the customers (Engelhardt et al., 2002). An investigation by AWWA (2008) found that US utilities may need to pay $250 billion over the next 30 years to maintain and replace ageing drinking water networks, including valves and fittings. In the current AMP (Asset Management Period 6, 2015-2020) cycle of the UK water industry, OFWAT, the financial regulator of the England and Wales water industry, has limited CAPEX at £44.3 billion, which is lower than the water companies predicted investment of £45.7 billion (OFWAT, 2014). These impractical amounts show the complex nature of investment and the end consumers to repay this investment over time. It is therefore expected that the water companies maintain the balance between total expenditure (TOTEX) including both CAPEX and OPEX and discolouration management strategies by considering long-term water quality benefits. This fundamental lack of knowledge drives this research work, which aims to take a holistic approach to investigate best discolouration management practices as part of water treatment works (WTW) outlet-to-tap approach, investigating the relevant long-term cost-benefit analysis.

1.1 Thesis Structure

Chapter 2 critiques and defines the relevance of state-of-the-art discolouration processes, modelling and management strategies. This chapter also explores what existing rehabilitation tools are available and the typical performance criteria that may or may not impact on discolouration risk processes. From the critical evaluation conducted in the literature review, knowledge gaps in managing discolouration risk and how to model the risk proactively have been identified. It is to be noted that several literature review sub-chapters are also included in the other chapters as background information.

Chapter 3 states the aims and objectives of the thesis.

Chapter 4 explores the long-term impact of flow conditioning intervention on discolouration risk from water treatment outlet to the downstream distribution network by assessing acute and chronic loading conditions. By collecting and analysing systematic long-term (+12 months) field data, this chapter presents for the first time how a network discolouration risk behaves under series of controlled interventions and different material loading conditions in the distribution network.

Chapter 5 evaluates the impact of an invasive cleaning intervention (ice slurry pigging) on water quantity (hydraulic roughness) and water quality (discolouration risk). This novel study enlightens our understanding about the complex interaction of pipe roughness and discolouration risk with the application of invasive intervention.

Chapter 6 assesses the long-term impact of planned (flow conditioning) and unplanned (bursts) hydraulic events on chlorine wall decay. This is a first ever attempt to evaluate how long-term applied shear stress on the pipe wall correlates with chlorine wall decay.

Chapter 7 discusses the simulation processes of long-term discolouration behaviour and validation of the Variable Condition Discolouration (VCD) modelling approach. A novel methodology is developed to collect required long-term field data and simulated in the VCD to test its ability to fit to the measured response. This is the first validation of accumulation functionality that encapsulated in the VCD model from field observed behaviour.

Chapter 8 presents a novel whole life costing (WLC) model to design flow conditioning cleaning intervention by trading intervention cost and hydraulic resilience. The exponential relationship derived from Pareto front solutions between cost and hydraulic resilience demonstrates the model ability to use it as decision support model. In this chapter, a methodology is also proposed that can incorporate material accumulation rates in WTW improvement to design trade-off for CAPEX of treatment works upgrade against OPEX of cleaning intervention and hence propose an enhanced discolouration risk management process for the drinking water network.

Chapter 9 presents cross-chapter discussions for chapter 4-8 and explores some future research direction.

Chapter 10 concludes all the findings from the research.

2. Literature Review

2.1 Why discolouration is an issue

Discolouration is the most frequent cause of water quality-related customer contacts worldwide (Vreeburg and Boxall, 2007). Customer contacts are often used as the key performance indicator by water utilities and their regulators (Polychronopolous et al., 2003). In Scotland alone, discolouration issues were reported in about 70% of total customer contacts in the year 2013, and 55% in 2015 (DWQR, 2014, 2016). Similar percentages of contacts have been seen in other parts of the world, e.g. England and Wales, Australia, USA, Canada, The Netherlands and France (Boxall and Prince, 2006; Deb et al., 1995; Ellison, 2003; Gauthier et al., 1999; Ginige et al., 2011; Husband, 2010; Ryan et al., 2008; Slaats et al., 2004).

Discoloured water is primarily considered to be aesthetically poor water (Vreeburg and Boxall, 2007). Failure of turbidity standards can be readily visible to the customer and will affect their confidence in the service provider. Depending on the customer contact performance, UK water companies can be fined or rewarded, and hence a drive to reduce customer contacts is vital for the water companies. Figure 2 shows typical discoloured water conditions from tap water. This poor aesthetic water quality can increase the consumption of bottled mineral water as an alternative (Baffoe-Bonnie, 2010). High turbidity concentration can contain increased levels of certain metals. Several flushing investigations reported a strong correlation between turbidity and Iron (Fe) and Manganese (Mn) (Boxall et al., (2003b), Cook (2007), Polychronopolous et al., (2003), Prince et al., (2003), Seth et al., (2004). An elevated level of Fe or Mn can be visible to consumers as “reddish” and “black” colours. Based on flushing data from several district metered areas (DMAs), predominantly from unlined cast iron (CI) mains, Cook (2007) demonstrated that about 70% discoloured particles are iron or forms thereof. He also showed that the prescribed Fe concentration value (PCV) limit in drinking water (200 μg/l) was exceeded when turbidity reached only 0.6 NTU. Similar results regarding excess Fe and Mn concentration were found in trunk main flushing data (Seth et al., 2010).

Figure 2: Discoloured water in households and its aesthetic conditions. (Image courtesy: www.inhabitat.com *and* www.drinktap.org)

2.1.1 Health impact

Discolouration is typically considered an aesthetic issue, but several researchers have demonstrated its potential impact on health. Various researchers have reported that raised levels of turbidity potentially correlated to gastrointestinal illness (GI) and often mask health issues (Mann et al., 2007; Morris et al., 1996; Schwartz and Levin, 1999; Tinker et al., 2008). Schwartz et al. (1997) found an association between regular turbidity in drinking water and endemic GI illness among children in Philadelphia.

Recent studies by Hsieh et al., (2015) found a positive correlation between turbidity response and the increase of diarrhoea patient visits. However, this increase was observed only in the spring and the authors suggested conducting more rigorous research to better understand the correlation. Higher levels of turbidity can reduce the disinfectant residual in the system, e.g. free chlorine and chloramine, which to some extent promotes microbiological activity (Allen et al., 2008; DWQR, 2013; LeChevallier et al., 1981; McCoy and Olson, 1986; WHO, 2006). High levels of turbidity can encourage the growth of pathogens and leading waterborne diseases (USEPA, 1999). Several studies indicate that there is a significant relationship between turbidity and removal of protozoa from the downstream water sample (Fox, 1995; LeChevallier and Norton, 1992; LeChevallier et al., 1993; Ongerth, 1990). However, this has not been conclusively proven.

2.2 Regulations

Discoloration in drinking water is a known cause of solid particle movement in the distribution system (Boxall et al., 2001; Seth et al., 2004; Vreeburg, 2007). It is usually measured in Nephelometric turbidity units (NTU), which determine particle concentration from a 90° scattering angle. In practice the turbidity limit in drinking water is set to a maximum of 4.0 NTU at the consumer's tap and 1.0 NTU at the WTW outlet (DWI, 2010; DWQR, 2013; Scottish Water, 2014; WHO, 2006, 2011). The Council of the European Union (1998) suggested that turbidity should be below 1.0 NTU at the treatment outlet in case of surface water treatment. An increased level of turbidity, typically above 4.0 NTU, could be visible to the customer and is not aesthetically acceptable (NHMRC, 2004; Slaats et al., 2004).

2.3 Nature and characterisation of discolouration materials

A particle size distribution analysis by Boxall et al. (2001) reported that discolouration is a particulate issue, but these particles are so small that they do not entirely follow the traditional sedimentation processes. The particle count analysis has shown that 70% (by count) particles found are 50 μm in diameter or less. In the Netherlands, particle diameter was found between 3-12 μm (van Thienen et al., 2011) and in the Australian distribution system this was approximately 11 μm (Ryan et al., 2008).

The specific gravity of discoloured material was reported between 1.0 and 1.3 in the UK distribution system (Boxall et al., 2001), while the average specific gravity in the Australian system was about 1.64 (Ryan et al., 2008).

In the UK distribution systems, turbidity is found to be correlated with Fe and Mn concentration (Boxall et al., 2003b). The ratio of metal (Fe, Mn and Al) concentration collected at different levels of excess shear stress and from different pipe materials has been found to be similar, indicating that the chemical composition of discolouration material is uniform regardless of discolouration material layer (Cook and Boxall, 2011).

Substantial organic content is also found from discolouration material samples, indicating its microbiological affiliation (Gauthier et al., 1999). Carriere et al. (2005) reported based on flushing data that 14-24% of particles were organic in nature. Similar results were found in Zacheus et al. (2001) and Sly et al., (1990) study. Distribution of bacteria has been shown to be correlated with turbidity, metals and phosphates in one UK distribution system (Douterelo et al., 2016). In Barbeau et al. (2005), sample collection during hydraulic disturbance showed that both total suspended solids (TSS) and turbidity correlated significantly with bacterial concentrations ($P<0.01$). It was hypothesized in this study that the discolouration particles may provide additional microbial nutrients for biofilm. The particle associated bacteria (PAB) may also accumulate as a loose deposit on the drinking water pipe wall, which may contribute to turbidity responses during hydraulic disturbance (Liu et al., 2016).

2.4 Role of biofilms in discolouration risk

Previously, discolouration thought to be an inorganic particulate issue (Cook and Boxall, 2011; Seth et al., 2004), although substantial percentage of organic material has indicated microbial affiliation (Gauthier et al., 1999). Recent studies suggested that Extra Polymeric Substances (EPS) composed of biofilms cells may play a vital role for discolouration process (Husband et al., 2016). The EPS is considered to hold floating inorganic-organic particles and create a robust protected environment for microorganism against the impact of disinfection (Cowle et al., 2014; Douterelo et al., 2014). Similar to DWDS cohesive layer theory, EPS has been identified as a cohesive, three dimensional polymer structure that is mobilised with increases in shear stress at the pipe wall (Abe et al., 2012; Choi and Morgenroth, 2003; Flemming and Wingender, 2010; Percival et al., 1999). The stratified characteristics with weak layer on top of biofilms similar to inorganic accumulated material has been found in previous studies as well (Derlon et al., 2008). Rochex et al., (2008) research reported that high shear stress decelerate biofilm maturation process and support to maintain young biofilm. However, it is also reported that regular detachment can be beneficial for biofilm diversification and bacterial populations (Percival et al., 2014). Fish et al., (2017) demonstrate that hydraulic regime did not have any significant impact on biofilms bacteriological composition, however, it does influence the mechanical stability of biofilms structure.

The regrowth of biofilms on DWDS pipe walls has been observed ubiquitously even under the presence of disinfectant conditions (Momba et al., 2000) and irrespective of pipe material (Hallam et al., 2001). Chemical analysis also suggests that the inorganic material can bind on EPS via cation ion exchange processes (Flemming and Wingender, 2010) and correlation between biofilms and iron and manganese deposition has been observed previously (Ginige et al., 2011). The presence of discolouration material around the pipe circumferences suggests that biofilm plays a key role for ubiquitous nature of discolouration material on pipe surface and provide support framework for inorganic incorporation.

2.5 Sources of discolouration material in distribution systems

The modern WTW produces high-quality potable water, although particles remain in the treated water transported from the WTW outlet to the point of use. Even with 0.1μm ultra-filtration, the particles can remain present in the distribution system (Vreeburg et al., 2008). Due to the complex physicochemical and microbiological reactions between bulk water and pipe wall, particles can be produced during the transit of water. Formation of particles is a very complex process and is not yet properly understood (Vreeburg, 2007). The discoloured material originates from various sources such as incomplete removal of particles from the treatment works e.g. raw water (Chandy and Angles, 2001), water filtration and coagulation process (Polychronopolous et al., 2003; Prince et al., 2003), powdered activated carbon (Brazos and O’Connor, 1996), aluminium flocks (Slaats et al., 2004; Cook and Boxall, 2011). Material may also enter on the distribution system cause of negative transients (Besner et al., 2010; Collins and Boxall, 2013), poor maintenance and repair (Slaats et al., 2004), internal processes e.g. iron corrosion (Sarin et al., 2002, 2003; Carriere et al., 2005; Cook, 2007;), chemical reactions (Kirmeyer, 2000; Sly et al., 1990) and biological growth (LeChevallier et al., 1987; Gauthier et al., 2001; Meckes, 2001).

2.6 Discolouration processes

2.6.1 Material mobilisation processes

(The following section has been taken from chapter 7)

Discolouration was traditionally conceptualised as the re-suspension of gravity-driven sediments. Extensive study of discolouration particle size distribution and density analysis revealed that the particles responsible are small in size and between 2-50 μm (Boxall et al., 2001; Ryan et al., 2008; Vreeburg, 2007). Hence self-weight effects are small and when re-suspended, they only settle due to the gravitational effects during prolonged quiescent conditions (Boxall et al., 2001). Similar phenomenon is suggested by UKWIR, (2001) that below 60 μm particles are prone to remain suspended unless quiescent conditions occurs. Particle accumulation alone by traditional gravity settling processes is also not considered valid in water distribution systems as flow is mostly in turbulent conditions (Blokker et al., 2010) and no sedimentation effect was found for a typical stagnation period in a dead-end pilot-scale areas (Smith et al., 1999).

Discolouration events are typically observed following hydraulic disequilibrium (Blokker and Schaap, 2015a). This change of network hydraulic conditions, e.g. burst or demand rezoning, may increase velocity and therefore shear stress (τ_C) higher than the pipe network recently experienced. This will cause detachment of particles into the bulk flow and hence create discolouration as this propagates downstream (Boxall et al., 2003b; Husband and Boxall, 2010). Flushing fieldwork has demonstrated that each step increase of shear stress releases additional material suggesting the accumulated material exhibits cohesive strength properties and are structured in varying strength with weaker layers mobilising earlier than stronger ones (Boxall et al., 2001, 2003b; Husband and Boxall, 2010). On the contrary, if material is comprised of loose deposits as conceptualised by sedimentation, all material will release instantaneously. A number of investigations have demonstrated particle mobilisation in response to velocity and shear stress and concluded that particles cannot bind in non-cohesive conditions unless the peak velocity is sufficiently low (Pothof and Blokker, 2012; Vreeburg, 2007). This suggests that accumulating material likely has cohesive properties, a result consistent with findings from the University of Sheffield fully temperature controlled experimental pipe facility (Husband et al., 2008).

2.6.2 Material accumulation processes

(The following section has been taken from chapter 7 and chapter 8)

In several repeated flushing trials, it has been seen that following flushing discolouration material returns, accumulating again on the pipe wall (Blokker and Schaap, 2015a; Cook and Boxall, 2011; Husband and Boxall, 2011; Husband et al., 2010). Repeated flushing also showed amounts of accumulated material during flushing was similar irrespective of seasonal influences suggesting material accumulated linearly over time (Boxall et al., 2003a; Cook and Boxall, 2011).

A number of studies have been aimed to develop an understanding of the material accumulation processes and how it is influenced by other physical, chemical and microbiological processes. Van Thienen et al., (2011) proposed two different accumulation mechanisms, turbophoresis and turbulent diffusion. Both these concepts only describe material transport from bulk water to wall and not how material bind on the pipe wall. These methods are not also applicable for large diameter pipes where turbophoresis is found influential to relatively large particles (>50 μm) and turbulent diffusion applicable only for very low velocities (<4 cm/s). Several researchers have provided evidence that discolouration material accumulates at varying strength cohesive layers at the same time (Husband and Boxall, 2011; Sharpe, 2012). Flushing field work by Husband and Boxall, (2011) in different parts of the UK demonstrated that material released in repeated flushing trials was lower than an initial flushing, indicating that accumulated material had not been completely regenerated after 12 months intervals. Their study, using multiple shear stress step increases, also showed material being mobilised at each step similar to the initial flushing trial. This repeated turbidity response supporting that material accumulation occurring simultaneously across the range of shear strengths. Accumulation processes observed in field studies have also been supported by laboratory trials in a full-scale temperature controlled pipe facility by Sharpe (2012). This study showed material mobilisation occurring across the range of imposed shear stresses with a consistent turbidity response, indicating particle binding on the pipe wall occurring simultaneously for all shear strengths. While varying strength simultaneous accumulation observed for small diameter pipe, it is still not tested for large diameter trunk main systems. From all the studies reported, it is evident a continual mobilisation-accumulation cycle exists that has a relatively consistent behaviour across the full range of shear strength bound material and applied hydraulic forces. This leads to complex material conditions on pipe walls and varying amounts of material could present on pipe wall with different cohesive shear strengths at any given time. Although knowledge of mobilisation and accumulation processes has been gathered from experimental investigations, no known modelling framework encapsulates these simultaneous effects which can then facilitate simulating the long-term turbidity behaviour.

2.7 Quantifying discolouration risk

(Part of this following section has been taken from chapter 4 and chapter 8)

Several studies quantified discolouration risk in the distribution system by assessing the rate at which material accumulates on pipe walls. These studies compared volumetric material loading (flow and turbidity) from repeated controlled hydraulic events, e.g. flushing, over a specified period (Vreeburg et al., 2008; Blokker et al., 2011; Cook and Boxall, 2011; Husband and Boxall, 2011; Blokker and Schaap, 2015a). Some studies investigated material accumulation return interval for distribution pipes of less than 150 mm (6”) reported between 1.5 and 4.0 years through repeated flushing

(Husband and Boxall, 2011) and 1.5 years with resuspension potential method (RPM) trials (Vreeburg et al., 2008). While Husband and Boxall, (2011) estimated based on annual repeat flushing frequency, Vreeburg et al., (2008) extrapolated the return rate from repeated RPM trials information. Richardt et al., (2009) developed a flushing decision model based on pipe specific turbidity potential for estimating possible flushing return intervals and found between 0.5-8.0 years. Assessing return interval using flushing or RPM methods is particularly complex for trunk mains due to their critical nature and the flows required. Therefore little information is currently available about material return interval for large diameter pipe systems.

Several studies proposed the importance of continuous turbidity measurement as part of a water quality monitoring program (Frey and Sullivan, 2005; Kara et al., 2016; Storey et al., 2011). van den Hoven et al. (1994) suggested that continuous turbidity measurement can be an indicator of aesthetic issues; for example, if turbidity increases during low demand periods, relevant pipes may need to be cleaned or re-lined to improve water quality. High temporal turbidity measurement was used to assess mass flux into the downstream distribution system and to identify spatial and localised material accumulation, suggesting its importance (Gaffney and Boult, 2012; Starczewska et al., 2017). By applying the CANARY event detection system (USEPA, 2010) to the turbidity data collected by Gaffney and Boult (2012), Mounce et al. (2015) showed that continuous turbidity coupling can be used with hydraulic data for an event detection indicator. While the current practice to track long-term turbidity is primarily based on DMA scale, none of the studies measures continuous turbidity from trunk mains for quantifying material loading into downstream DMA. Therefore, the risk from upstream trunk main to downstream DMA is not quantified yet and still not well understood.

2.8 Potential influencing variables of discolouration risk

The water distribution network is a complex reactor where numerous bulk water constituents react with the pipe wall in physicochemical and microbiological processes. The material mobilisation and accumulation process is also part of this complex reaction process. Several researchers have investigated the factors that could influence the both material accumulation and mobilisation process and have found that asset characteristics and source water quality significantly influence accumulation conditions or discolouration risk (Cook and Boxall, 2011; Husband and Boxall, 2011; Lehtola et al., 2006), while hydraulics profoundly effect on mobilisation processes. Given the complex network conditions and operational practicalities, it is still unknown how the accumulation rate independently differs due to each variable. Hence, the factors influencing the accumulation rate and discolouration risk should consider in relative rather than absolute terms.

2.8.1 Source water and bulk water quality

(Part of this following section has been taken from chapter 4)

The type of source water and the bulk water quality have shown significant impact on the material accumulation process. Husband and Boxall (2011) repeated a flushing study in the UK-wide water network and demonstrated that a surface water-supplied network is typically regenerated to its initial conditions within 1.5 years following flushing, whereas this takes about three years for a groundwater-supplied network. To remove the natural organic matter (NOM) from raw water, it is a common practice to dose a Ferric (Fe) or alum (Al) coagulant (Sharp et al., 2006a, 2006b). However, failure to remove the coagulant particles means they could pass through the WTW outlet and may affect the network discolouration risk (Cook and Boxall, 2011). Husband and Boxall (2011) have further shown that a lower discolouration risk is found in non-coagulant systems compared to coagulant systems, where discolouration risk increased from alum-based to ferric-based coagulants.

Many researchers investigated the influence of bulk water on discolouration risk by assessing material accumulation rates. Blokker and Schaap (2015) studied the material accumulation rates in two similar networks over a six-year period and found accumulation rate was variable with changing water source highlighting water quality as a factor. Cook and Boxall, (2011) found that accumulation rates were consistent between two DMAs fed from the same source suggesting water quality importance on accumulation rate. Bulk water was found to be a key factor for discolouration risk in non-corroding pipes (Husband and Boxall, 2011). Vreeburg et al., (2008) demonstrated that even with ultra-filtration (UF) treatment, particles exist in the network, however, accumulation return interval could be extended up to 10-15 years suggesting the implication of treated water quality and microbiological interaction with water constituents. Husband and Boxall, (2010) further explored the bulk water significance on material accumulation, and they proposed two material accumulation mechanisms influenced by 1) bulk water quality and 2) corrosion processes. Both accumulation mechanisms imply that all pipes in normal operation are susceptible to cohesive layer development and hence pose discolouration risk.

Other processes at the WTW could also influence the discolouration risk in the downstream network. A decrease in pH may accelerate the corrosion process within the distribution systems (McNeill and Edwards, 2001), influencing discolouration risk.

Adding disinfection, e.g. chlorine and chloramine in drinking water to control microbial contamination and biofilms, is a common practice around the globe (Fisher et al., 2011; Hallam et al., 2002; Ramos et al., 2009; Vasconcelos et al., 1997). However, this disinfectant concentration can oxidise the soluble Fe and Mn and precipitates, which could further increase the discolouration risk in distribution systems (Sly et al., 1990). This is difficult to control, as the rate of chlorine decay is reported to be increased by nitrate concentration, temperature (Li et al., 2003; Zhang and Edwards, 2007) and other factors e.g. TOC, pH. Hence balancing or tuning the process at the WTW is essential to reduce the risk of discolouration in systems.

2.8.2 Pipe hydraulic conditions

(Part of this following section has been taken from chapter 4)

Several studies have shown that material settles and accumulates differently in a laminar hydraulic regime than a turbulent one (Pothof and Blokker, 2012; Vreeburg, 2010). Gaffney and Boult (2012) showed based on long-term turbidity monitoring in two DMAs at various locations that flushing does not inevitably reduce material loading in bulk water, suggesting that wall-bound layer conditions did not improve by applied shear stress conditions. Starczewska et al. (2017) demonstrated an overall improvement in DMA material transport (decrease>0.5 NTU flux) after flushing at one site. However, at another site where the network had relatively higher water flow, an increase in small flux (<0.3 NTU) was observed. By applying the CANARY event detection system (USEPA, 2010) to Gaffney and Boult (2012) turbidity data, Mounce et al. (2015) found that flushing significantly reduces the frequency of turbidity events. While both studies had used same dataset, results can be varied subject to analysis and interpretation.

2.8.3 Network characteristics

A water distribution network (WDN) is comprised of a vast buried pipe network which may have a wide variety and heterogeneity of pipe material. In the early 19th century, most pipes installed were cast iron (CI). Since 1970 a variety of plastic pipes have been installed (Momba et al., 2000) around the globe, which are thought to have a positive impact on water quality. The material accumulation rate has been found to be more rapid in CI mains than the smooth pipe systems, indicating the significance of pipe material (Husband and Boxall, 2011). Their study suggests that material may regenerate to its initial conditions following a flushing intervention by about two years for a CI main. The same risk to regenerate in a smooth pipe could take up to four years. These findings are supported by the idea that CI mains contributes additional material accumulation through corrosion processes (Cook and Boxall, 2011; Husband and Boxall, 2010).

2.8.4 Temperature and microbial properties

Temperature as an independent variable affects a range of water physical and quality parameters, e.g. chlorine decay (Li et al., 2003), fluid dynamic viscosity (Nguyen et al., 2007) and microbial properties (Hallam et al., 2001). However, little is understood about how temperature affects discolouration risk. Blokker and Schaap, (2015b) found a correlation between particle accumulation and seasonal water temperature when assessing data from multiple flushing of the Dutch water network. Sharpe (2012) explored the effect of temperature on material accumulation in full-scale laboratory conditions by providing material accumulation conditions at 8°C and 16°C for 28 days. She observed that the highest material mobilisation occurs at relatively higher water temperature (16°C). It has been hypothesised (Burns and Stach, 2002; Douterelo et al., 2013) that discolouration particles may provide microbial nutrients for biofilm and be trapped in the extracellular polymeric matrix, a key component of biofilms. While temperature influences microbiological properties, it is anticipated that temperature plays a critical role for discolouration risk as well. Previous work also suggested a microbial influence on the discolouration process (Ginige et al., 2011; Husband et al., 2016).

2.8.5 Pressure

Apart from other physical processes, no correlation of discolouration risk with pressure has been found in any previous studies. Gaffney and Boult (2012) collected pressure and turbidity event data from multiple sites and found no significant correlation. The lack of interest in the effect of pressure on accumulation processes has been influenced by the fact that the shear stress or velocity is not significantly affected by absolute pressure.

However, the study by Aisopou et al. (2010) did suggest that unstable hydraulics could contribute to a discolouration response. They used the Vardy-Brown shear stress model to assess the impact of material mobilisation on discolouration material. The unsteady shear stress was much higher than the steady-state shear condition, although quantification of such temporally transient and associated response impacts is critical to investigate. Recently, Weston et al. (2017) demonstrated the transient event can potentially impact on material mobilisation, however, it is still not properly understood the mechanism and how such event influence the accumulation process.

2.9 Modelling discolouration in water distribution system

In recent times, discolouration modelling and prediction have captured significant interest, especially in the UK water industry, where discolouration management is of major importance in terms of water quality improvement. The complex interactions between the various bulk water components and pipe walls make the discolouration process exceptionally complex. Hence it is advisable to design the model with the key dominant process. While the mobilisation process is observed mostly from hydraulic disturbance, the accumulation rate on pipe walls is far more complex and depends on several factors, e.g. bulk water, pipe material, hydraulics, temperature and microbiology. Hence it is a challenge to develop an appropriate discolouration model capturing varying effects without making the model overly complicated.

2.9.1 Prediction of Discolouration in Distribution Systems (PODDS) Model

In 2001, The Prediction of Discolouration in Distribution System (PODDS) model was developed (Boxall and Saul, 2005) based on the idea that particulate material adheres ubiquitously as cohesive layers on all boundary surfaces with a layer shear strength conditioned by the maximum daily prevailing hydraulics (τ_d). These cohesive layer shear strengths remain in equilibrium conditions by balancing with the daily maximum applied shear stress (τ_d).

The discolouration potential in the PODDS model designed as:

$$\tau_c = \frac{C^b - C_{max}}{k} \quad (1)$$

Where,

τ_c = Current material layer strength [N/m^2]

C = Stored volume of material on the pipe wall [$NTU.m^3$]

C_{max} = Maximum material volume for a fully developed layer [$NTU.m^3$]

b = A power term, although later it found to be unity as no model fitting benefits was observed other than unity (Husband, 2010).

k = Gradient of discolouration potential compare to layer shear strength and can contribute to increasing turbidity

The rate of material supply is described as:

$$R = P(\tau_a - \tau_c)^n \quad (2)$$

Where,

τ_a - τ_c = Excess applied shear stress [N/m^2]

R = Rate of supply from unit wall area [$NTU.ms^{-1}$]

P = Linear coefficient of force required to erode [$NTU.m^3.N^{-1}.s^{-1}$]

n = exponential coefficient of force required to erode [-]

The rate of supply further defines the change in turbidity during mobilisation and subsequent decrease in discolouration potential.

$$\Delta N = \frac{R.A_s}{Q} \quad (3)$$

Where,

ΔN = change in turbidity [NTU]

A_s = Area of pipe wall [m^2]

Q = Bulk flow [m^3/s]

The PODDS model was coded in the open-source EPANET (Rossman, 2000) by revisiting its water quality engine (Boxall and Saul, 2005). The discolouration material released from the pipe wall is initially calculated by the PODDS governing equation, and the EPANET Lagrangian transport algorithm is then used to track the fate of particles along the pipe and mixing at the junction throughout the network.

The PODDS material mobilisation process was coded as material mobilised from the weakest to the strongest layer based on the field evidence (Boxall and Saul, 2005). The PODDS model functionality was successively validated in the UK for both DMAs (Cook and Boxall, 2011; Husband and Boxall, 2010) and trunk main systems (Husband and Boxall, 2015; Husband et al., 2010). The model output was further fitted to flushing data captured from Australian asbestos cement pipe, highlighting its universality (Boxall and Prince, 2006).

During the model implementation in EPANET, the accumulation process was coded as a reverse process of mobilisation (strongest to weakest layer). It was designed based on the authors' engineering judgement, to facilitate the model formulations in the software, and not based on any field data or observation (Boxall and Saul, 2005). Although the model mobilisation process was validated, accumulation processes do not follow the laboratory or field evidence (Husband and Boxall, 2011; Sharpe, 2012) suggesting the model limited applicability for simulating long-term discolouration behaviour. Figure 3 shows a typical PODDS model output to the measured response of the trunk main. A set of calibrated model parameters was compiled in a look-up table indexed with pipe material, diameter and length. The intellectual property right (IPR) to this dataset is held by the PODDS project stakeholders (www.PODDS.co.uk) and the model is not publicly available at this moment.

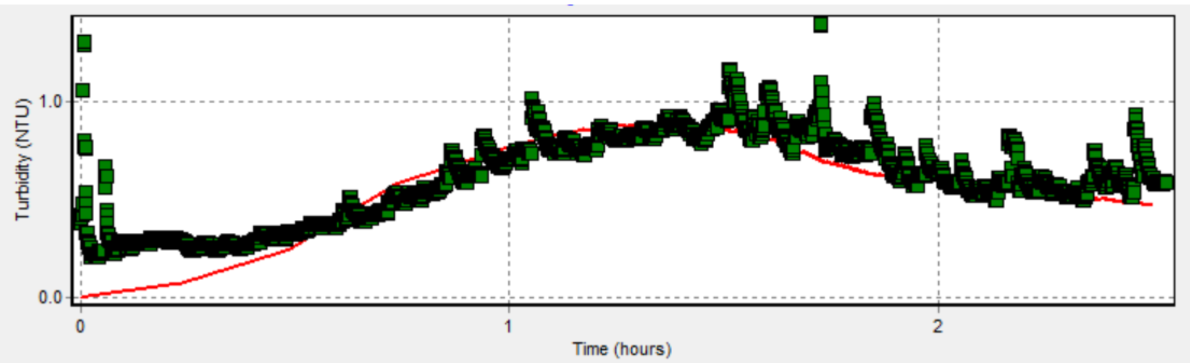

Figure 3: PODDS model graphical representation and calibration of a trunk main simulated (red line) and measured turbidity response (green dot). Measured data was collected from a separate flow conditioning trial for Scottish Water and not published previously.

2.9.2 The Variable Condition Discolouration (VCD) model

(The following section has been taken from chapter 7)

In 2014, Furnass et al., (2014) proposed the Variable Condition Discolouration (VCD) model to simulate the discolouration behaviour as observed from laboratory and field data. The model captures some key mechanisms which govern discolouration as:

a) The model assumes that wall bound cohesive layers remain in equilibrium conditions with recent prevailing hydraulics (τ_c).
b) Material at the pipe wall accumulates over full range of shear strength when applied shear stress (τ_a) $<\tau_c$
c) Material is mobilised from the pipe wall and entrained and completely mixed with the bulk water due to the imposed excess shear stress (τ_a-τ_c) when $\tau_a>\tau_c$. In this context, the VCD model retains the same mobilisation mechanism as the PODDS model (Boxall and Saul, 2005).
d) Model is designed to track material across the range of shear strengths with mobilisation and accumulation processes occurring simultaneously.
e) The model assumes material adheres uniformly throughout the pipe wall adopting field evidenced flushing data (Boxall and Saul, 2005).
f) Model assume weak layer is always on top of stronger layers

The model tracks relative material quantity φ (τ,t), a unitless parameter, bound between [0,1.0] where 0 means no material and 1.0 is a maximum accumulation of material (Furnass et al., 2014). The VCD model simulates discolouration using three empirical parameters, a mobilisation rate = β_e [$N^{-1}m^{-2}s^{-1}$], an accumulation rate = β_r [s^{-1}] and material release coefficient = α [NTU.m.s^{-1}]). The mobilisation rate (β_e) and material release coefficient (α) describe the material mobilisation phenomenon and represent the rate of material release from a pipe wall where β_e is a function of excess shear stress (τ_a-τ_c), and α is linear scaling parameter. The accumulation rate (β_r) describes the rate at which material accumulates on the pipe wall and is a pipe specific property. To reduce modelling complexity, all three model parameters (β_r, β_e, α) are currently designed as a scaler and invariant with time and shear strength.

Furnass et al., (2014) verified the VCD model through synthetic data and then successfully calibrated it for small diameter pipes and a single trunk main from field data. The calibration results demonstrated that the VCD model retains the mobilisation function of the PODDS model, with similar quality of fitting obtained. Suitable data was not available to validate the accumulation functionality for the small diameter pipes, and the trunk main dataset was limited by the quality of the long-term time series data. Thus the accumulation mechanism of VCD model is verified (Furnass, 2015; Furnass et al., 2014), but has not been validated with long term data. The validation of accumulation process (occurs at all cohesive strengths simultaneously) and hence validation of VCD model would allow tracking discolouration response for different hydraulic scenarios and how risk changes over time and can be minimised.

2.9.3 Other discolouration model

2.9.3.1 The Discolouration Risk Model (DRM) and Discolouration Propensity Model (DPM)

The discolouration risk model (DRM) is a risk assessment modelling approach to identify the likelihood of discolouration propensity due to the hydraulic events and structural failure throughout the network (Dewis and Randall-Smith, 2005). DRM has been used as an integral part of Yorkshire water asset management plan. A major modelling difference compared to PODDS is that it uses dynamic velocity changes rather than shear stress variation, which limits its modelling inaccuracy during a change of pipe diameter and roughness height (Cook, 2007). Unlike the PODDS model, a burst likelihood function has been integrated for risk analysis. However, it is limited to “expert judgement” to assign weighting criteria for the burst score analysis.

The discolouration propensity model (DPM) is the successor of the DRM to quantify rank-based discolouration risk and provide further support to decide on appropriate cleaning interventions (McClymont et al., 2011, 2013). Instead of a velocity-driven mobilisation process, DPM adopted the PODDS cohesive transport model (Boxall and Saul, 2005) and discolouration risk quantified based on the maximum shear stress applied to the pipe wall. The DPM embedded with the Epanet hydraulic solver and a full-scale hydraulic model can be incorporated to identify the maximum discolouration risk from any unusual shear stress events. While both models use hydraulic to describe discolouration risk, neither of the models has yet been validated.

2.9.3.2 The Particle Sedimentation Model (PSM)

The particle sedimentation model (PSM) was developed by a team from CSIRO (Australia) to predict the particle mass and distribution conditions in the water distribution network (Ryan et al., 2008). The PSM adopted both gravitational and non-gravitational particle accumulation concepts on the pipe wall, where the latter attracts particles by Van der Waals forces. It was assumed that if critical velocity is higher than bulk water velocity during the gravitational setting process, particles are suspended from the pipe wall. They observed a velocity of around 0.15-0.25 m/s, material re-suspended from pipe invert sections and all suspended material mobilised equal to or greater than 0.3 m/s water velocity. The PSM explained material accumulation on the pipe circumference by Fick's law of diffusion.

$$\frac{\partial C}{\partial t} = -\alpha(C - C_\infty)$$

$$C_w = \beta C_\infty$$

Where, C = Particle concentration in bulk water	[ppm]
C_w = Particle mass in pipe wall	[ppm]
C_∞ = Final steady state particle concentration	[ppm]
α= Decay coefficient	[unit less]
β = Wall mass coefficient	[unit less]

If $C< C_\infty$: Particle accumulation from bulk water to the pipe wall

If $C> C_\infty$: Particle mobilisation from wall

If $C= C_\infty$: No particle resuspension or accumulation

However, since a research report published in 2008 regarding the model construction and verification, no reference has been made to the PSM. The model has not been validated with large samples or tested in different systems. The model uses gravity deposit processes, which is contrary to the operational evidence (Boxall et al., 2001; UKWIR, 2001). The PSM also does not purely account for hydrodynamic conditions (Armand et al., 2015) and its inability to explain the process of material adhered on pipe wall restricts its applicability (Furnass, 2015).

2.9.3.3 Artificial neural network (ANN) model

Meyers et al. (2017) used the artificial neural network (ANN) technique to forecast discolouration conditions as an early warning system. The proposed model could forecast turbidity events 15 minutes in advance. The model is understood to be a fully data-driven process, and hence there are no requirements for a hydraulic or water quality model. However, this proposed ANN model does not describe discolouration processes and has not been tested in a variety of networks and is therefore currently not transferable across sites.

2.9.3.4 Material accumulation investigation through data-driven model

Mounce et al. (2014) used the evolutionary polynomial regression (EPR) model combining flushing and an asset dataset to derive a relative material accumulation rate on the pipe wall. They used 13 predictor variables for discolouration process with an estimate of relative accumulation rate. Repeated flushing data for 67 individual pipe lengths was used to estimate the relative accumulation rate. They found that background iron concentration, pipe material, looped network and pipe volume had the greatest impact on material accumulation rate. The accuracy of the proposed data-driven model depends on the quality and amount of the data, as well as the numbers of predictor variables with consistent data available.

Danso-Amoako and Prasad (2014) used the ANN technique to investigate Fe and Mn accumulation potential and hence further network discolouration risk potential. Initially, the dataset was studied to build an ANN model consisting of water quality data from 176 different DMAs with 37 individual parameters, although this was later reduced to 15 parameters. The model simulation suggests that aluminium concentration in bulk water between 0-120 μg/l could facilitate an increase of Fe and Mn accumulation potential, with a slight decrease when concentration exceeded 120 μg/l. They found that an increase of calcium carbonate ($CaCO_3$) decreases Fe and Mn accumulation potential. The free chlorine results showed mixed effects on Fe and Mn accumulation and suggested maintaining 0.8 to 1.8 mg/l to reduce the accumulation potential. However, it is understood from the available literature that the study findings are limited without the additional input of physical properties, i.e. shear stress, pipe material, etc.

2.9.4 Summary

(The following section has been taken from chapter 7)

There are various models that can simulate the material mobilisation processes, but none of the models is yet able to simulate material accumulation conditions. Unlike other discolouration models, the PODDS model has an integrated material accumulation function that is the reverse of the mobilisation process. However, the accumulation process coded in the PODDS model does not describe the behaviour observed from the laboratory (Sharpe, 2012) and field data (Husband and Boxall, 2011) that has been collected and analysed since its inception. Considering the limitations of previous models, the VCD model can simulate both mobilisation and accumulation processes continuously and accumulation at all strengths simultaneously. Although the model accumulation functionality has been verified (Furnass et al., 2014), it still requires validation.

2.10 Trunk main impact on downstream discolouration risk

The transmission or trunk main is typically a large-diameter pipe that transports water from WTW to the downstream consumer or service reservoir. In recent decades DMAs have been given the most operational attention as they are connected directly to the end consumers (Aikman, 1993). However, recent operational works have looked more and more closely into larger pipe diameters. Discolouration knowledge and management techniques are particularly important for trunk mains because unplanned operational events, e.g. bursts and/or valve movement, can impact hundreds of downstream consumers. Research has indicated that trunk mains play an important role in discolouration risk to the downstream consumer. In 2013-14, unplanned intervention in the trunk main initiated discolouration or particle-related issues affecting 2-3 million consumers in the UK (DWI, 2014). Long term clustered discolouration customer contact analysis suggested that around 30-50% of contacts were initiated based on the trunk main and/or upstream boundary of DMAs (Husband et al., 2010; Cook et al., 2015). In the UK and international water industry, cast iron pipes are still predominant in trunk main system. From the cast iron pipes, corrosion can supply additional discoloured particles in the downstream distribution zone. Hence the risk is relatively higher from trunk main to multiple DMAs and not well understood.

Due to strict operational and quality regulation, water companies worldwide often avoid operational activities associated with trunk mains (Husband et al., 2014). Cleaning operations in a trunk main can be complex due to its critical layout and lack of redundancy. With the conventional techniques e.g. invasive cleaning and relining, trunk mains require isolation that may cause supply disruption. While non-invasive cleaning interventions e.g. flushing have been implemented successfully in the DMA system, it has some drawbacks for trunk main operation implementation. In practice, trunk main flushing is not common due to the high volume of water usage during the flushing procedure and wastewater disposal management issues. Trunk mains are often very long, and hence the pipe turnover is potentially long enough to affect the upstream storage or downstream wastewater compartment. Hence it is desirable to implement an intervention for trunk main that have in-service functionality and can manage water disposal issues.

2.11 Discolouration management strategies

To mitigate discolouration and other water quality risks in trunk mains, water companies regularly implement various network maintenance interventions, e.g. flushing, invasive cleaning, relining or pipe replacement (Engelhardt et al., 2000). Most of the network maintenance is based on reactive responses, which means mains cleaning is only scheduled based on customer complaints about water quality and/or asset structural conditions. While invasive cleaning is widely popular among water companies for ongoing maintenance, there are non-invasive techniques available that have also been reported to manage discolouration risk.

2.11.1 Pipe replacement and relining

Typically, unlined CI mains are considered the highest risk for discolouration due to the potential release of Fe content in bulk water from corrosion layers. Husband and Boxall (2011) demonstrated based on UK-wide flushing studies that plastic pipes have longer material accumulation period or pose lower discolouration risk than relatively rough mains, e.g. unlined CI. In the UK, a substantial percentage of pipe material consists of unlined CI, but each company have their own replacement programme. While pipe replacement may improve water quality, due to the cost and operational constraints involved with the entire process water companies often hesitate to undertake such programmes. As an alternative to the pipe replacement, relining is a popular process among water companies. While North American companies tend to use cement mortar lining, European companies prefer epoxy and polyurethane lining (Water Research Foundation, 2010). Study shows that relatively high concentrations of metals, e.g. aluminium, calcium and chromium, as well as pH, than under normal conditions was found from lined main (Water Research Foundation, 2010). Both pipe replacement and relining can be very expensive. In Canada water companies spent about $28 billion from 1997 to 2012 as part of network rehabilitation strategies, showing the extent of investment required (Shahata and Zayed, 2010). Although a substantial amount of money is spent on this type of strategy, there is no evidence that it improves long-term discolouration risk.

2.11.2 Invasive cleaning

2.11.2.1 Air scouring

The air scouring method uses compressed air to blow into an isolated water main to break down the accumulated layer, biofilms and soft scales (Smith, 1999). The method is used to clean by a mixture of air and water which is forced into one end of the pipe section (Ellison, 2003). Compressed air provides the turbulence to the existing water to clear the accumulated material, soft scale and biofilms. The compressed air may also include atomized chlorine and a polyphosphate inhibitor (Smith, 1999). Air scouring is popular in the UK water industry. Figure 4 shows a typical air scouring method to clean accumulated material.

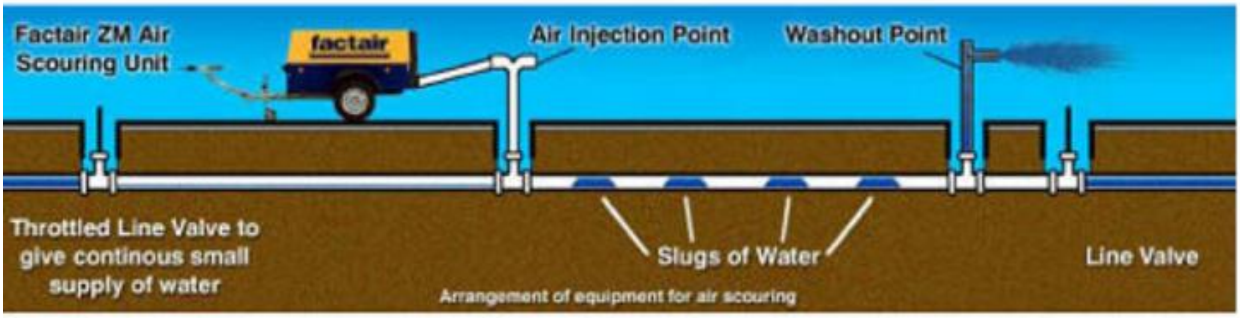

Figure 4: Typical air scouring method and slug flow to clean the deposits (Image courtesy: USA Ltd, 2014)

This procedure requires 40% less water than a typical swabbing and flushing program, removes more scales and deposits than flushing, and the pipe breakage rate is relatively low as the air pressure remains below the operating pressure (Ellison, 2003; WHO, 2004). The air scouring method is not classed as an aggressive method, although if the internal structure of the pipe is not in good condition then it can create leakages and expose the unlined corrosion layer (Ellison, 2003).

2.11.2.2 Swabbing

Swabbing is a type of "polyurethane cylindrical foam sponge" pig technique to remove the wall-bound material and biofilms from the network using water pressure. Swabbing is one of the most known cleaning procedures, and hence the effectiveness of this method is well documented (Ellison, 2003; Friedman et al., 2012; WHO, 2004). A "swab" is a particular type of pig used to clean larger pipe diameters (Ellison, 2003). Normally, these pigs are 25% larger in diameter than the nominal diameter of the pipe section, which creates a frictional shear force into the pipe wall to remove attached material (Friedman et al., 2012). Three different grades are available for swabbing: soft, hard and scouring (WRc, 1994). Swabbing is an effective intervention when the velocity of water is between 0.8 and 1.5 m/s, where the pigs are move in tandem with the water velocity and have enough time to apply the desired shear stress on the pipe wall (WHO, 2004).

2.11.2.3 Ice pigging

Ice pigging technology is a comparatively new pipe cleaning method which consists in inserting designed ice slurries into the pipe with a desired flow rate to remove the accumulated pipe wall materials. The semi-solid ice creates shear stress on the pipe wall and hence mobilised wall-bound accumulated material. Figure 5 shows a typical ice pigging operation where a semi-solid ice slurry is inserted from an upstream access point and highly turbid water is collected from a suitable downstream access point. During the process, collected highly turbid water is constantly monitored via bottle sampling and water temperature, and conductivity is also tested as part of the scheme. Ice pigging can remove material from pipes of diameters ranging from 15 mm to 300 mm and as long as 2 km (Bristol Water, 2014). Ice pigging is a patented technology initially developed by the Bristol University Research Centre as a potential alternative pipe cleaning process (Berriman, 2011; Quarini, 2002). This technology is currently used by different water suppliers around the globe, including some UK water utilities. Several studies have reported that the ice pigging considerably reduces biofilm and accumulated particles, requires less water and time, and does not block mains, as the ice simply melts away after a while (Candy et al., 2010; Evans et al., 2008; Moore, 2013; Quarini et al., 2010). The ice plug consists of 50-90% crystal ice and the mixture of ice-water designed in such a way that it moves in the main as a solid plug and can move with water in constricted areas (Quarini, 2002).

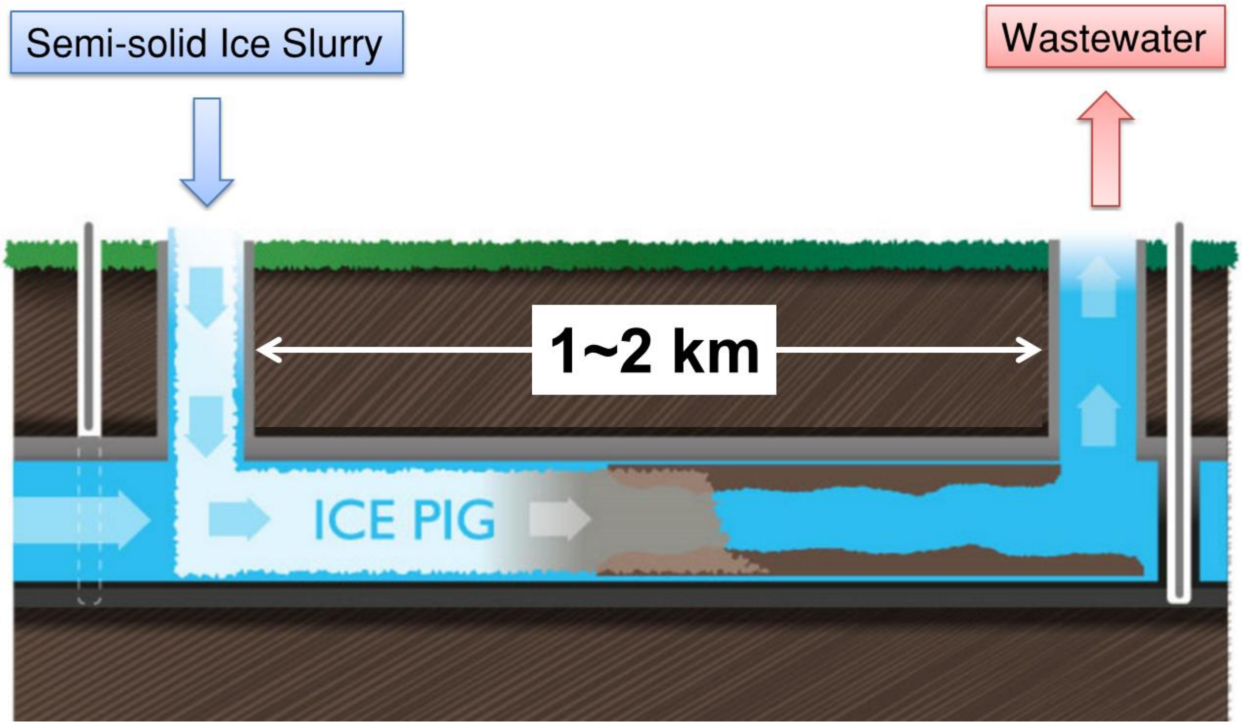

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Figure 5: Procedure of ice pigging strategy in a selected pipe (image courtesy: Yarra Valey Water)

Candy et al. (2010) showed that ice plugs lose pressure at the start of the trial at a higher rate than the end of the trial, indicating higher resistance from ice plug generated at the top section of the pipe. A pressure drop during ice plug movement through pipe channel was reported by Shire (2006) as well. The loss of friction force during transit can limit its effectiveness in removing wall-bound material. Ice pigging is less expensive than other invasive cleaning techniques, e.g. swabbing and air scouring, but it requires high operational expertise and equipment. It also requires more intensive planning to ensure no other water is drawn into the main to dilute or disturb the ice slug formation (Friedman et al., 2002).

2.11.3 Non-invasive cleaning

2.11.3.1 Self-cleaning velocity concept

Self-cleaning velocity is the critical velocity that considers limiting material accumulation on pipe walls. This force is applied in a daily frequency that inhibits the build-up of the material layer. Water companies from the Netherlands have practiced this threshold velocity concept since 1999 (Slaats et al., 2004; Van Den Boomen et al., 2004; Vreeburg and Van Den Boomen, 2002). Slaats et al. (2004) suggest that 0.4 m/s is sufficient to prevent material accumulation, while Ryan et al. (2008) observed that material started to mobilise at 0.3 m/s or higher. Boxall and Prince (2006) found 1.12 N/m^2 as a consistent value in the Australian network and 1.2 N/m^2 in the UK water network systems (Husband and Boxall, 2010). Blokker et al. (2010) reported that the Dutch water companies found 0.25 m/s to be sufficient for a variety of pipe materials.

To demonstrate and validate the self-cleaning velocity principle, Blokker et al. (2007) analysed these methods in several types of distribution networks. They found that branched networks are better at self-cleaning than looped systems. In a conventional distribution network, velocities are moderately low or even stagnant (Blokker et al., 2006) and this stagnation is dominated by fire flow demand (Vreeburg, 2007). According to Vreeburg et al. (2009) this method is cost-effective for newly built systems and can reduce the expenses by 20% compared to the conventional Dutch water network.

The aforementioned studies were conducted in plastic pipe systems only. The findings are also limited to small-diameter mains. Since higher velocity or shear stress conditions already exist in trunk main systems, it is difficult to assess self-cleaning conditions for trunk mains. Another important consideration is the future development of water demand in the selected areas. This may lead to further increase of expansion costs to maintain the threshold velocity. To implement this method, co-ordination is required with the firefighting demand.

2.11.3.2 Flushing

Flushing is the oldest conventional and robust operational cleaning technique adopted by water suppliers to improve water quality. It is widely used to remove accumulated pipe material at the DMA level. Pipe dead ends in distribution systems are common places for water quality degradation, material deposition and bacterial growth (Barbeau et al., 2005). The flushing procedure is mainly divided into conventional and unidirectional flushing (UDF) (Nilsson et al., 2008). Conventional flushing consists in opening a fire hydrant with the desired flow rate as long as the pre-selected water quality is reached with no valve control (Hasit et al., 2004). A drawback of the conventional system is that it operates without controlling the selected valve closure options. Therefore, the highly turbid water can move to any other location of the network. The UDF method operates by closing valves and opening hydrants in a strategic manner (Ellison, 2003). A survey was conducted by Hasit et al. (2004) among 26 water utilities around the world and found that only 36% used the UDF method and

37% used conventional flushing. The remaining 27% used both methods. WRc (1998) proposed flushing velocity guidelines for different pipe diameters derived from the loose sediment transport theory. In practice, DMA flushing operation is undertaken at night to reduce the customer water usage impact and dissatisfaction. Night-time flushing operations can utilise the maximum available pressure while the base water flow level is minimum. UDF flushing frequency is subject to the best management practices (Friedman et al., 2002) with site-specific velocity and increase of customer contact in a specific region (Carriere et al., 2005). However, the dead end distribution system flushing process is still predominantly brought about by customer complaints (Barbeau et al., 2005).

Flushing has shown a number of water quality-related benefits over the short term, e.g. it minimises customer complaints, reduces public health-related problems and maintains the structural condition of the pipe (Hasit et al., 2004). However, it is reported not to be very effective in cleaning heavily tuberculated pipe sections (Ellison, 2003).

2.11.3.3 Flow conditioning approach

(Part of this following section has been taken from chapter 4, 5 and 8)

A cohesive transport model was proposed by Boxall et al., (2001) that discolouration layer binds on pipe wall ubiquitously and has varying cohesive strength properties. Based on this theory an in-service trunk main cleaning strategy termed “flow conditioning” was developed by the University of Sheffield collaborating with several UK water companies (Husband and Boxall, 2015). The flow conditioning can be described as “controlled in-service flushing” based on knowledge of historical hydraulic and network properties and managing the impact of increasing shear stress.

The method is designed to operate under operational network conditions without interrupting supply and therefore, maximum 1.0 NTU is targeted during the trial to avoid any potential turbidity prescribed concentration value (PCV) failure in the downstream network. This is achieved by imposing an excess system shear stress (τ_a-τ_i) until all material with strength below the imposed shear stress is mobilised. The remaining material is then considered “conditioned” to this imposed excess shear stress and would require further increases in shear stress to be mobilised. Use of multiple flow conditioning steps and manage the response at each stage allows target flows, or the desired system resilience, to be achieved. As a result, this strategy can be used to prevent discolouration risk from both planned and unplanned events, e.g. rezoning and bursts. In this case, resilience means the magnitude of hydraulic event that will cause minimal or no discolouration response.

This cleaning intervention has been effectively and successfully implemented in several trunk main systems with proven reduction in discolouration risk (Cook et al., 2015; Husband and Boxall, 2015).. However, the long-term impact on the trunk main and the downstream network discolouration risk is unknown. During flow conditioning, mobilised material is entrained in the bulk flow as wash load and transported through the downstream network and ultimately to the point of use. There is concern that the periodic mobilisation and transport of acute material (> typical average turbidity reading) loads during flow conditioning event could accelerate accumulation in the downstream network increasing discolouration risk. This additional material mobilised from pipe wall transported for only a short period of time (few minutes to hours depending on hydraulic conditions) compared to continuous turbidity or chronic loading. Therefore the primary research concern with the flow conditioning intervention is that periodic acute material loading or bulk water chronic loading may influence downstream discolouration risk more, which is not investigated yet.

Similar to accumulated material cohesive nature, biofilms have been identified as a cohesive, three-dimensional polymer structure that can be mobilised with increases in shear stress (Abe et al., 2012). Recent studies suggested that biofilm may play a vital role for discolouration process (Husband et al., 2016) which is considered to hold floating inorganic-organic particles and creates a robust protected environment for microorganism against the impact of disinfection (Cowle et al., 2014). Research indicates that chlorine penetration is limited into the biofilm matrix and have a reduced efficacy against biofilm microorganisms (Chen and Stewart, 1996; De Beer et al., 1994). Therefore by mobilising the top weak biofilm layer along with cohesive material layer during shear stress events potentially expose fresh biofilms which is a concern that it could increase the chlorine wall decay due to the new wall condition. While the flow conditioning has been proven to be good for controlling discolouration risk, the aim is to explore if it has any impact on chlorine wall decay.

Flow conditioning is a relatively cheaper alternative compared to the other known maintenance strategies as it only uses system hydraulics to manage discolouration risk and no specialist tools are required for operation. Unlike other rehabilitation techniques, flow conditioning requires only OPEX, and it can be implemented in a range of network conditions, e.g. in normal operation or new pipes, however, no model has been developed yet that can simulate OPEX of this intervention.

2.5.6 Summary

Among the currently available rehabilitation techniques, invasive cleaning processes are well-known to water suppliers. Invasive cleaning can remove significant amounts of accumulated material from the operational main and improve water quality (Friedman et al., 2012; Quarini et al., 2010; Smith, 1999; WHO, 2004). However, they are relatively expensive and require skilled manpower and specialised equipment. Some of these techniques are quite aggressive and can cause internal structural deterioration of pipes. In general, during invasive cleaning processes mains need to be taken out of service and networks must rezone via valve movement or back-feed to provide a continuous water supply, which can cause significant customer disruption. For rezoning purposes, valve movement is a common practice in the water industry, although it is thought to generate discolouration responses (Cook, 2007). In the UK, significant percentages of the pipe networks are comprised of unlined cast iron. Since most of the techniques are invasive, their application can pose high discolouration risk by disturbing the existing corrosion layer.

While short-term applications of invasive cleaning to minimise discolouration risk are well known, long-term benefits have yet to be investigated. Due to the continuous material accumulation (Boxall et al., 2003a; Cook and Boxall, 2011), one-off applications of these cleaning interventions are not considered a long-term strategy. Hence it is ideal to implement periodic interventions with some prior knowledge of material accumulation processes. While the non-invasive cleaning strategies, e.g. flow conditioning and self-cleaning velocity, can be implemented periodically, their long-term impact on discolouration risk remains unknown.

2.12 Modelling of rehabilitation strategies and discolouration risk

(Part of this following section has been taken from chapter 8)

In the UK, selection of drinking water pipe rehabilitation techniques is primarily driven by the short-term benefits and cost (Marlow et al., 2015). However, for cost optimisation, it is sensible to account for all relevant costs and benefits throughout the distribution main service life. Pre 1970, infrastructure investment decisions relied heavily on capital cost alone (Boussabaine and Kirkham, 2008). Later, WLC concepts were developed based on the idea that OPEX for any asset maintenance could be higher than its CAPEX. The WLC term has been defined in BS/ ISO 15686-5 Buildings & Constructed Assets:

"an economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability….

This is a methodology for the systematic economic consideration of all whole life costs and benefits over a period of analysis, as defined in the agreed scope"

Several researchers demonstrated WLC approach for water distribution networks to minimise total expenditure (TOTEX) that includes both CAPEX and OPEX for a required level of service by maximising desired performance (Conroy and Hughes, 1997; Engelhardt et al., 2002; Skipworth et al., 2002; Jayaram and Srinivasan, 2008). For water quality improvement, water utilities typically exercise different types of rehabilitation techniques, e.g. pipe replacement, relining of old cast iron (CI) main, invasive cleaning. Rehabilitation decision and prioritisation models to address structural performance and water loss have been developed using diverse performance criteria, e.g. burst rate and asset age (Engelhardt et al., 2003), integrating GIS, hydraulic data and breakage models (Tabesh and Saber, 2012), use of cost function based on pipe replacement, rehabilitation, repairs and pumping cost (Kim and Mays, 1994), and pipe failure and replacement cost using Bayesian parameter estimation (Scholten et al., 2014). The above-mentioned models were mostly focussed on structural performance and water quantity; none of the models considers water quality performance as a criterion. While replacing pipe or relining unlined CI mains can reduce discolouration risk (Engelhardt et al., 2000; Husband and Boxall, 2011), previous studies have not assessed their performance based on discolouration risk. It is also noted that bursts have a cleaning effect on pipe walls as they create a hydraulic disturbance and mobilise accumulated discolouration material. Cook (2007) observed after companywide long-term bursts assessment that there was a reduction in discolouration based customer contacts in the summer season following a higher number of recorded bursts during the winter period. However, forecasting bursts events and associated effects on discolouration risk is relatively complex to evaluate and not yet well understood and the corresponding model should encapsulate discolouration processes as well.

Primarily, the decision models compared CAPEX investment, e.g. installing new pipe, with ongoing OPEX, e.g. pipe repair, to hence minimise overall TOTEX. Skipworth et al. (2002) proposed a WLC methodology considering periodic flushing of distribution pipes to reduce accumulated material and relining of unlined cast iron mains (thereby removing a source of discolouration material from corrosion) to reduce the required flushing frequency. However, apart from the conceptual proposals, no further study on this WLC methodology has been reported. Most of these models have primarily been proposed or developed for small diameter pipes. However, large diameter pipes have relatively lower shear stress conditions and mixing of material due to the higher ratio of water volume to surface area can have a different effect on discolouration behaviour. Thus methodologies to manage trunk main discolouration risk or investigate associated TOTEX for trunk main interventions are as yet unknown.

2.13 Summary and knowledge gaps

The existing literature provides a wealth of information regarding discolouration processes, including material mobilisation and accumulation processes and how discolouration modelling analysis can be implemented to manage various operational techniques to control discolouration risk. In addition, types of cost framework available for water rehabilitation strategies are also discussed in the literature review section. Several knowledge gaps were identified based on the literature reviews that require further investigation. Particularly for this study some of the knowledge gaps are described below:

1. The literature review section has discussed different types of cleaning intervention for managing discolouration risk. While it was found that improving treated water quality can reduce material loading and hence improve discolouration risk, the trunk main intervention's impact on discolouration risk as part of a WTW outlet to customer tap approach has not been assessed. Since invasive cleaning strategies are complex to implement, some non-invasive strategies e.g. flow conditioning have the potential to manage long-term discolouration risk. A specific concern with flow conditioning intervention is that intervention process can initiate transport of occasional acute material loading from trunk main to downstream distribution network. However, none of the studies has ever undertaken to evaluate the impact of flow conditioning on trunk main chronic material loading and the difference between the chronic and acute loading on downstream network accumulation processes.
2. From research study, it is envisaged that biofilms have a similar cohesive structure to accumulated material which mobilises due to excess shear stress. By mobilising the top weak

biofilm layer along with cohesive material layer during flow conditioning events potentially expose fresh biofilms which is a concern that it could increase the chlorine wall decay due to the new wall condition. However, no previous studies have been undertaken to explore the impact of periodic flow conditioning on chlorine wall decay.

3. It is well established that invasive cleaning (e.g. ice pigging, air scouring, swabbing) can remove significant amounts of wall bound accumulated materials from operational trunk mains. However, little is quantified regarding the efficacy of such interventions in terms of either quantity e.g. pipe roughness or quality e.g. discolouration risk improvement and how this changes over time following the intervention.

4. The literature study describes various discolouration modelling techniques and their limitations. Most of the existing discolouration models are reported to simulate mobilisation processes; however, none of the models can simulate the material accumulation process. A detailed explanation is given for a newly verified model called variable condition discolouration (VCD) that can simulate both material mobilisation and accumulation processes continuously and accumulates at all strengths simultaneously. The mobilisation process of the VCD model has been validated, but the material accumulation processes have not. Therefore, the model's ability to simulate long-term discolouration behaviour has not yet been fully tested.

5. Due to continuous material accumulation, one-off intervention is not considered sustainable, as it can impact the on-going OPEX. The cleaning interventions are typically very expensive, but these costs are limited through financial caps set by the regulators. It is desirable for water companies to minimise intervention costs through modelling methods. The literature study assesses different existing models that use various performance criteria to optimise the OPEX of water rehabilitation strategies, but none of the models includes discolouration processes and material accumulation rate or return period as decision criteria. Thus a design process is required to identify the cost to manage discolouration risk and maintain network discolouration risk resilience against any hydraulic event.

3. Aim of the Thesis

The overall target of this research is to prepare a framework for long term cost-effective holistic discolouration management practice for water distribution network. The central aim of the research is to explore how controlled interventions can be best applied in trunk mains to manage long-term discolouration risk from a water treatment outlet to downstream distribution zone approach. The research hypothesis is that the trunk main flow conditioning intervention is the cost-effective long-term discolouration management strategy.

3.1 Thesis objectives

To achieve the overall aim, research objectives were discretely divided, yet coherent in total structure. Each objective was set as clear and concise to accomplish the target aims.

1. To explore the impact of trunk main flow conditioning intervention on long-term discolouration risk by investigating the change in chronic material loading of trunk main and difference between the effects of chronic and acute material loading from trunk main on downstream network accumulation return period. (chapter 4).

2. To investigate the long-term impact of periodic flow conditioning intervention on chlorine wall decay (chapter 5).

3. To investigate the quantity and quality performance benefits of an in-service trunk main invasive cleaning program (chapter 6).

4. To assess if the VCD model can simulate the long-term turbidity behaviour of operational trunk main systems and hence provide a useful tool for informing discolouration risk assessment and management (chapter 7).

5. To demonstrate how to design flow conditioning cycles to manage discolouration risk by trading cost against hydraulic resilience (chapter 8).

4. How Chronic and Acute Material Loading Impacts Discolouration Risk in a Water Distribution Network

Declaration

The chapter four is in a format that can be further developed and then be suitable for submission as journal paper. The contribution of the main author and co-authors are following:

1. **Iftekhar Zaman Sunny** is the PhD candidate and 1st author and major contributor to this published chapter. As a part of his PhD research, he has formulated the aims, developed the methodology, monitored and analysed necessary data and outlined conclusions for this publishable paper. Primarily he has designed and written the chapter having inputs from the co-authors as stated in point 2.

2. **Prof. Joby Boxall and Dr. Stewart Husband** are the primary academic co-authors of these chapters. They have supervised the PhD research project and provided critical input into the research methodology. They have helped to define and refine the aims, overall structure of the thesis, interpretation of results and formulation of discussion points. They also have provided necessary guidance on the chapter content and structure including grammar corrections and correcting sentence structure in order to clarify the sentence meaning.

Iftekhar Zaman Sunny 1st author	Dr. Stewart Husband 2nd author	Prof. Joby Boxall Last author

4.1 Abstract

The long-term impact of cleaning interventions on discolouration risk and how risk varies with different material loading conditions in a drinking water network is still unknown. This study presents the long-term impact of trunk main flow conditioning intervention on trunk mains and downstream network discolouration risk. An extensive approach of long-term continuous data collection from upstream to downstream network was undertaken through imposing a series of flow conditioning interventions on multiple trunk mains with similar characteristics, including a control main, and systematic analysis carried out to explore the impact of acute and chronic material loading. While flow conditioning increases occasional immediate acute material loading, simultaneously it reduces chronic loading from trunk mains compared to control. Overall evidence suggested that chronic loading on the downstream network is significantly influential on material accumulation rates and hence discolouration risk than the short term elevated acute loading from flow conditioning events. Thus, the evidence demonstrated that trunk main flow conditioning can improve both trunk main and downstream network discolouration risk by reducing overall trunk main chronic material loading. This novel understanding of acute and chronic loading impact on overall discolouration risk suggests that relatively cheaper non-invasive techniques, e.g. flow conditioning intervention, can be a viable management option leading to better use of aged infrastructure and providing better quality water for the customer.

Keywords: Flow conditioning, shear stress, discolouration risks, accumulation rate

4.2 Introduction

Drinking water distribution systems (DWDS) are high surface area reactors where a complex set of physical, chemical and biological interactions occur simultaneously in both the bulk water and at the pipe wall. Impacts include discolouration, a key factor affecting customer satisfaction and acceptability of drinking water, due to the mobilisation of particulate material accumulated at the pipe wall. Often discolouration events are short in duration and associated with hydraulic disturbance. Discolouration samples could breach the other water quality parameters’ regulatory limits, e.g. iron concentration (Cook, 2007). In the UK, substantial financial penalties and rewards depending on annual water quality performance have been set for the water utilities (DWI, 2016), with discolouration customer contacts identified as a primary quality target (Polychronopolous et al., 2003). Hence the significance of discolouration customer contact analysis is prominent for assessing performance against discolouration risk. Although customer contacts are typically recorded in downstream District Metered Areas (DMA), 30-50% of discolouration events origin have been identified from the upstream source or trunk main (Cook et al., 2015).

Large diameter pipes, e.g. trunk mains, are critical water distribution infrastructure from where the risk of discolouration is high due to the populations potentially exposed. Due to the fear of potential consequences from trunk main failure and associated strict regulations, the water companies are reluctant to undertake operational activities associated with them. The complexity of buried infrastructure access also influences the decision to avoid operational undertakings. However, to manage and deliver the highest drinking water quality standards to customers, interventions are becoming inevitable as infrastructure deteriorates and expectations rise. As a result, water utilities are regularly investing in the cleaning of accumulated materials from trunk mains to improve water quantity and quality as part of their rehabilitation programs. An option to clean the wall-bound material legacy is through expensive, invasive cleaning strategies, e.g. air scouring, ice pigging or swabbing (AWWA, 2014). These strategies may deliver short-term water quality benefits yet it is often difficult to implement such expensive and specialist resource-oriented strategies due to the challenge of taking trunk mains out of service without interrupting supply. In many cases, discolouration material returns on the pipe wall (Cook and Boxall, 2011) and water quality contacts (Boxall et al., 2003a) in those networks, questioning the long-term benefits of such invasive strategies. Some non-invasive and in-service hydraulic driven cleaning interventions have been implemented successfully in the distribution system, e.g. flow conditioning (Husband and Boxall, 2015), self-cleaning velocity technique (Van Den Boomen et al., 2004; Vreeburg et al., 2009). However, the long-term impact on discolouration risk of these non-invasive techniques has never been assessed. Also, how these non-invasive techniques influence discolouration risk from water treatment works (WTW) outlet to the downstream distribution network is still unknown. Therefore, there are concerns over whether and how these interventions influence long-term discolouration risk and provide water quality benefits throughout water distribution networks.

4.3 Background

4.3.1 Discolouration processes: Material mobilisation

Prior to 2001, discolouration was conceived to be the re-suspension of gravity deposit sediments. Particle size distribution (PSD) analysis showed that the particles responsible for discolouration are microscopic in size (2-50 μm). Discolouration particles are typically observed to be mobilised during hydraulic disturbances where each flow or shear stress step increase mobilises additional material during flushing investigations, evidencing that particles have cohesive properties where weak layers remain on top of stronger layers (Boxall et al., 2003b; Husband and Boxall, 2011). Boxall et al. (2001) hypothesised that these particles remain in equilibrium condition and mobilise during excess shear stress conditions. Several researchers (Vreeburg, 2007; Pothof and Blokker, 2012) concluded that particles cannot accumulate in a non-cohesive manner unless the peak hydraulic conditions are very low. The water distribution network (WDS) cohesive layer theory was previously validated under temperature controlled laboratory conditions (Husband et al., 2008) and for operational systems (Husband and Boxall, 2011, 2016).

4.3.2 Discolouration processes: Material accumulation

Several studies showed that discolouration material in WDS accumulated again on the pipe wall following flushing (Husband et al., 2010; Cook and Boxall, 2011; Husband and Boxall, 2011; Blokker and Schaap, 2015a). While those studies found that material mobilisation occurred from weak to strong cohesive layers, the reverse process of accumulation was not observed. The repeated flushing study conducted in the same pipes after a 12 months interval by Husband and Boxall, (2011) showed that turbidity response to each shear stress step increase was similar to the first or initial trial and suggested that material regenerates at varying shear strengths simultaneously. These material accumulation process findings were also supported by the fully temperature controlled laboratory-scale pipe network investigations by Sharpe, (2012). While simultaneous accumulation of varying strengths of material was observed for small diameter pipe, this has still not been tested for large diameter trunk main systems.

4.3.3 Quantifying discolouration risk

Several studies quantified discolouration risk in the distribution system by assessing the rate at which material accumulates on pipe walls. These studies compared volumetric material loading (flow and turbidity) from repeated controlled hydraulic events, e.g. flushing, over a specified period (Vreeburg et al., 2008; Blokker et al., 2011; Cook and Boxall, 2011; Husband and Boxall, 2011; Blokker and Schaap, 2015a). The accumulation return interval found in these studies ranged between 1.5 and 4.0 years. However, measuring accumulation rates in trunk mains using these methods is difficult due to their layout and the volume of water required.

Several studies proposed the importance of continuous turbidity measurement as part of a water quality monitoring program (Frey and Sullivan, 2005; Kara et al., 2016; Storey et al., 2011). van den Hoven et al. (1994) suggested that continuous turbidity measurement is an indicator of aesthetic issues; for example, if turbidity increases during low demand periods, relevant pipes may need to be cleaned or re-lined to improve water quality. High temporal turbidity measurement was used to assess mass flux into the downstream distribution system and to identify spatial and localised material accumulation, suggesting its importance (Gaffney and Boult, 2012; Starczewska et al., 2017). By applying the CANARY event detection system (USEPA, 2010) to the turbidity data collected by Gaffney and Boult (2012), Mounce et al. (2015) showed that continuous turbidity coupling can be used with hydraulic data for an event detection indicator. No studies have yet measured continuous turbidity from trunk mains for quantifying material loading into downstream DMA. Since the risk from upstream trunk main to downstream DMA has not yet been quantified, it is still not well understood.

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4.3.4 Bulk water significance on material accumulation rate

Research has shown that the return period of material accumulation or accumulation rate is influenced by several factors, e.g. raw and bulk water quality (Chandy and Angles, 2001; Cook and Boxall, 2011; Husband and Boxall, 2011), pipe material (Husband and Boxall, 2011), network hydraulic conditions (Pothof and Blokker, 2012; Sharpe, 2012), and water temperature (Blokker and Schaap, 2015b).

Many researchers investigated the influence of bulk water on discolouration risk by assessing material accumulation rates. Blokker and Schaap (2015) studied the material accumulation rates in two similar networks over a six-year period and found accumulation rate was variable with changing water source, highlighting water quality as a factor. Cook and Boxall (2011) found that accumulation rates were consistent between two DMAs fed from the same source, suggesting importance of water quality for accumulation rate. Bulk water was found to be a key factor for discolouration risk in non-corroding pipes (Husband and Boxall, 2011). Additionally, Vreeburg et al. (2008) demonstrated that even with ultra-filtration (UF) treatment, particles exist in the network; however, the accumulation return period could extend for up to 10-15 years, suggesting the implication of treated water quality. Husband and Boxall (2010) further explored the significance of bulk water for material accumulation, and they proposed two material accumulation mechanisms that are influenced by 1) bulk water quality and 2) corrosion processes. Both accumulation mechanisms imply that all pipes in normal operation are susceptible to cohesive layer development and hence pose discolouration risk.

4.3.5 Hydraulic based discolouration management strategy in trunk mains

A non-invasive trunk main cleaning strategy termed "*flow conditioning*" was developed based on the concept of a cohesive transport turbidity modelling approach (Husband and Boxall, 2015). This strategy was developed and implemented by the University of Sheffield in collaboration with several UK water companies. Flow conditioning is considered as "controlled in-service flushing" imposing managed shear stress to mobilise controled amounts of material, below the UK regulatory limit of 4.0 NTU. It requires having extensive knowledge of pipe hydraulic and properties prior to the trial. During flow conditioning, mobilised material is entrained in the bulk flow as wash load and transported through the downstream network and ultimately to the point of use. The method is designed to operate under operational network conditions without interrupting supply, and therefore, maximum 1.0 NTU is targeted during the trial to avoid any potential turbidity prescribed concentration value (PCV) failure in the downstream network. Material with cohesive strength higher than the imposed shear stress remains on the pipe wall and hence flow conditioning reduces discolouration risk by removing (weaker) material loading proactively from the trunk main pipe wall. Thus flow conditioning has the ability to achieve target hydraulic resilience by increasing shear stress to a certain level. In this case, resilience refers to the magnitude of hydraulic events that will cause minimal or no discolouration response. Meanwhile, not removing the stronger layers during flow conditioning may lead to the weaker layer accumulating more rapidly in the trunk main itself, hence risk could be higher after the intervention. However, this was not investigated in any previous works which is the scope of this study.

This cleaning intervention has been effectively and successfully implemented in several trunk main systems with proven reduction in discolouration risk (Husband and Boxall, 2015). However, the long-term impact on the trunk main and the downstream network discolouration risk is unknown.

There is concern that the periodic mobilisation and transport of acute material (> typical average turbidity reading) loads from trunk mains during flow conditioning events could accelerate accumulation in the downstream network increasing discolouration risk. This additional material is mobilised from the trunk main and transported for only a short period of time (a few minutes to hours depending on hydraulic magnitude and period) compared to the continuous turbidity flux or chronic loading time period of days to years. Figure 6 presents the acute and chronic material loading scenarios and material concentration during the transport from trunk main to downstream distribution zone. Therefore the primary research concern with the flow conditioning intervention is that periodic acute material loading or bulk water chronic loading may have more influence on downstream discolouration risk more, which has not been investigated yet. This study explores the impact of trunk main flow conditioning intervention on long-term discolouration risk by investigating the change in chronic material loading of trunk main and difference between the effects of chronic and acute material loading from trunk main on downstream network accumulation return period.

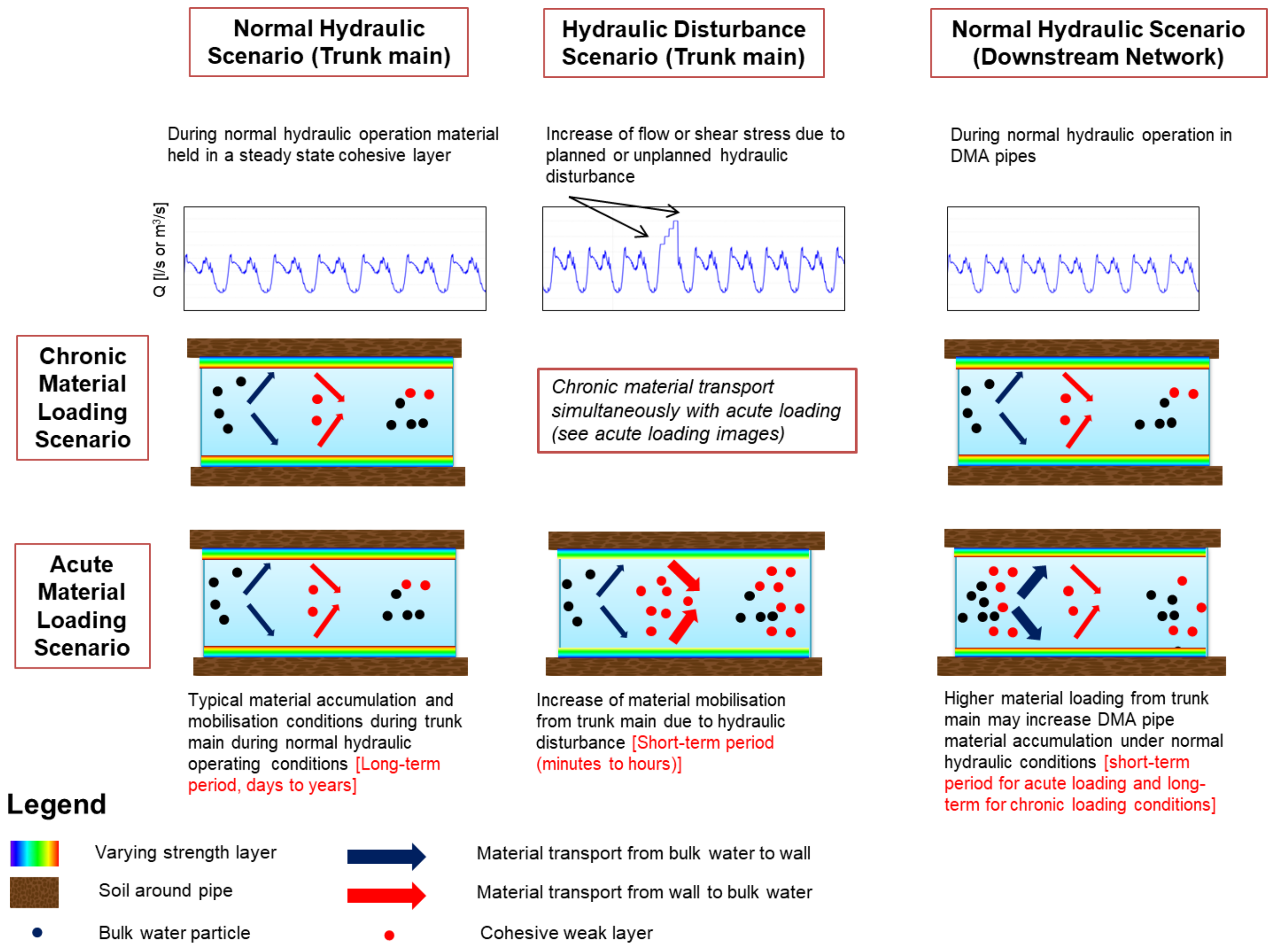


Figure 6: Chronic and acute material loading under varying hydraulic conditions

4.4 Methods and Materials

4.4.1 Methodology

A methodology was developed to investigate the change in chronic loading of trunk mains and address the effects of chronic and acute material loading on discolouration risk induced from flow conditioning intervention. In order to investigate this, it is required to obtain both long-term hydraulic and turbidity time series data that include different material loading scenarios from flow conditioning. To assess the impact of different material loading on downstream accumulation conditions, an investigation of mass flux variations of discolouration material in relation to imposed hydraulic conditions was essential.

Figure 7 presents the different magnitudes and periods of flow conditioning interventions applied on trunk mains. To provide the range of varying material loading scenarios and accumulation periods, two types of flow conditioning interventions were implemented periodically in two similar trunk mains: one with higher applied shear stress termed 'normal flow conditioning' and the other with relatively lower imposed shear stress termed 'passive flow conditioning'. Both interventions were implemented quarterly to get a measurable response (Figure 7). A similar third trunk main with no intervention was selected as a control and flow conditioning intervention implemented at time zero and after 12 months. These varying magnitude events from the three trunk mains ensured different loading scenarios from trunk mains to downstream network, and as a result different discolouration risk conditions in the downstream test networks.

The same initial imposed shear stress magnitude was used for the three trunk mains to set similar initial levels of discolouration risk conditions. The same final shear stress was applied to assess final discolouration risk for the three different maintenance strategies. Since different material loading was hypothesised to be transported from the trunk mains to downstream, it was likely that downstream material accumulation rates would be different. Thus from each trunk main, downstream distribution pipes with similar characteristics were flushed before and after all planned trials to assess material accumulation rates using mass flux analysis, as shown in Figure 7.

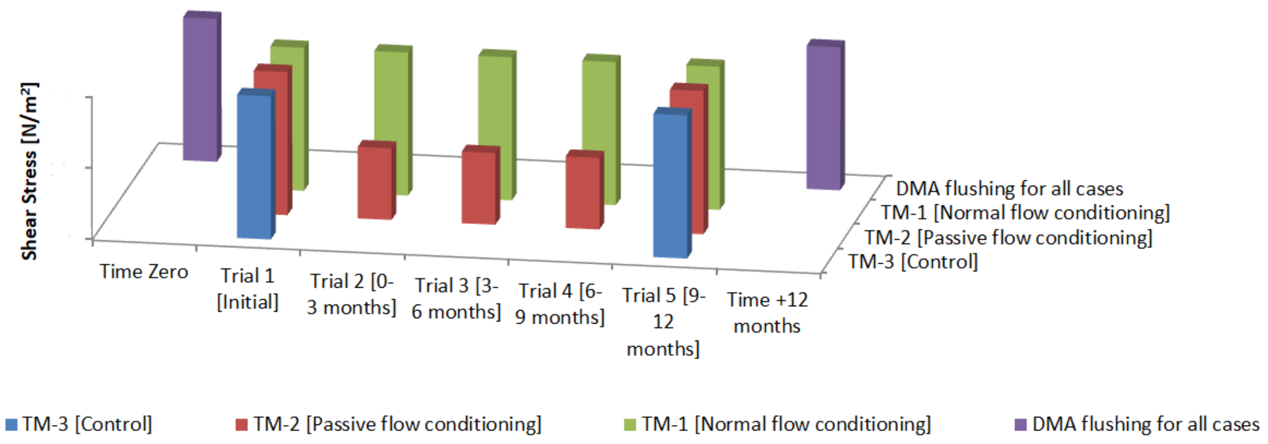


Figure 7: Fieldwork procedure, timeline and flow conditioning strategy definition where TM-1 is Normal flow conditioning, TM-2 is Passive flow conditioning, and TM-3 is Control. DMA flushing occurs in pipes downstream of all three trunk mains.

Both hydraulics and water quality data are essential for this study. Trunk main flow data are necessary to record and manage both normal and flow conditioning events. Turbidity data are required to assess the material loading from flow conditioning trials and during normal operating conditions, at the common inlet to the three trunk mains and the downstream end of each. Monitoring turbidity at high temporal resolution is necessary to capture continuous material loading which can produce a quantitative indication of water quality as turbidity variations. Repeated flow conditioning trial response was compared by calculating material mass flux using both flow and turbidity data. Observing continuous turbidity data can be used to quantify the material loading from trunk mains to downstream network; however, it cannot separate the simultaneous chronic and acute loading impact on the particles passing through the downstream pipes and accumulating on the pipe wall. Therefore, to quantify the impact of different loading on downstrean accumulation, material accumulation rates or return period were estimated from repeated flushing trials using mass flux analysis within the selected DMAs' pipes. It is to be noted that continuous turbidity measurement can only measure chronic and acute material loading and provide indication of how specific pipes perform against discolouration risk. However, it does not represent directly the amount of material that accumulates on the pipe wall.

In order to complete the experimental design, it is necessary to eliminate effects of other influential variables on material accumulation processes, such as source water, hydraulics, pipe material. Therefore, the test network was selected based on a single water source supplying the three trunk mains, similar hydraulic conditions and similar pipe material. For downstream repeat flushing investigations, similar pipe properties were selected, e.g. similar hydraulics, pipe material and location in the network to provide comparable material accumulation rates.

4.4.2 Site details and network characteristics

To fulfil the experimental design, a treatment outlet to tertiary (downstream) water network was selected from a UK based operational drinking water distribution network. Three independent trunk mains each supplied from a single treated water source, were selected for the case study. Each trunk main had similar pipe material and hydraulics profile, e.g. velocity, Reynold number and shear stress. This was to ensure comparable physical, chemical and microbiological water quality condition and hence discolouration risk between each main prior any intervention. Figure 8 presents the network schematics with monitoring instruments location. While the choice of inlet point confirmed the incoming loading from treated water, the outlet point monitors ensured that the monitoring section covered the change of discolouration risk within the trunk main over time and interventions and hence could provide accurate material loading information to the downstream network.

The instruments as shown in Figure 8 were deployed in such a way that they could capture the necessary information for this study, described in the methodology. In addition to continuous turbidity and flow data, discolouration based customer contact data from the DMAs were collected to provide further collaborating insight and impact of different loading conditions. While customer contact is based on the consumer’s visual perception, the numbers of contacts per 1000 properties can be an indicator for DMAs discolouration risk performance and hence it is treated as secondary data for this study.

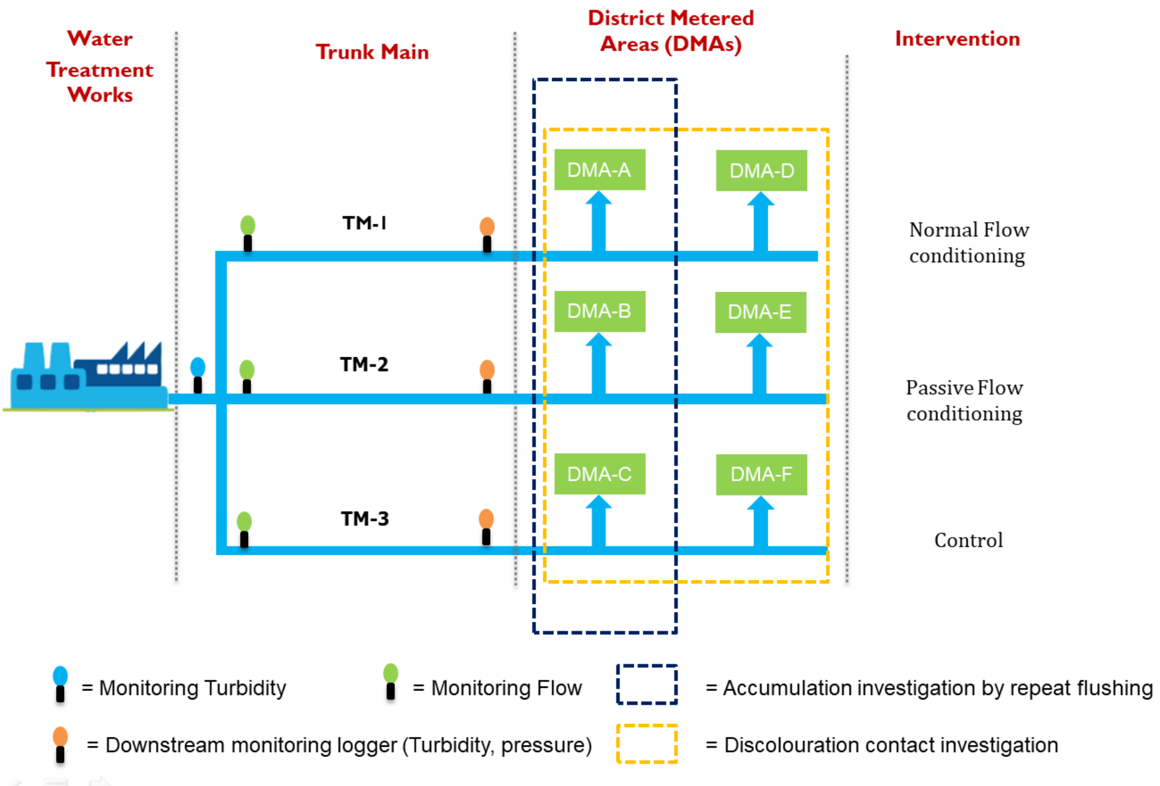


Figure 8: Network layout including water treatment, the three supplied trunk mains and DMAs layout and deployed instruments locations where a Sigrist Aquascat 2 turbidity meter was used for upstream and ATI Nephnet and Evoqua Hydraclam were used for downstream continuous turbidity measurement and ABB Aquamaster was used for continuous flow measurement.

Table 1 presents the physical and typical hydraulic properties of the three test trunk mains.

Table 1: Trunk mains hydraulic properties where CI = Cast Iron

Trunk main system	Mean internal diameter from industry record [mm]	Pipe material	Length from WTW outlet to downstream logger [km]	Calibrated Pipe Roughness, k_s [mm]	Velocity [m/s] min, average, max	Shear stress [N/m^2] min, average, max	Reynold number [-]*10^4 min, average, max
TM-1	304.8	Partially lined CI	6.4	8.50	0.4, 0.6, 0.8	0.1, 1.0, 2.0	4, 8, 15
TM-2	406.8	Unlined CI	5.6	10.35	0.1, 0.3, 0.4	0.1, 0.7, 1.7	4, 8, 14
TM-3	304.8	Unlined CI	5.9	7.50	0.2, 0.4, 0.6	0.1, 1.0, 2.2	5, 9, 13

The raw water was supplied from an upland surface source and treated with a ferric coagulation process. Table 2 presents the treated water quality parameters from discrete samples collected for regulatory purposes from 2013 to 2016. All mains were gravity fed from the treatment works.

Table 2: Treated water quality parameters values; discrete samples collected from January 2013 till May 2017 ($n \geq 200$)

Treated water quality parameters	Unit	Average	Min	Max	Standard deviation
Iron (min 0.45 µm filter)	µg/l	23.0	7	100	16
Manganese (min 0.45 µm filter)	µg/l	1.8	1	6	1.0
Aluminium (min 0.45 µm filter)	µg/l	39.0	9	57	10.6
Turbidity	NTU	0.1	0.05	0.9	0.03
Total Organic Carbon (TOC) (min 0.45 µm filter)	mg/l	1.7	0.6	2.8	0.5
Free Chlorine	mg/l	1.4	0.5	5	0.3
Water temperature	°C	9.6	0.7	18	4.7

4.4.3 Selected DMAs pipes characteristics

As part of company network maintenance, all DMAs within the operational area including the selected DMAs were flushed before the investigations. In total five pipes with similar characteristics were chosen from each of the selected DMAs for repeated flushing. Priority was given to the non-corroding pipes, such that the dominant contribution to discolouration risk would be accumulation from the bulk water, rather than local contribution from corrosion of the pipes themselves. All pipes were located near to the inlet of DMA and operated as dead end sections serving residential areas, so had similar demand patterns, rather than serving further different sized downstream areas. The flow in the investigated pipes was typically diurnally variable and relatively consistent across the year, with sub-daily variations. Table 3 presents the properties of selected pipes for flushing analysis.

Table 3: Test DMA pipes physical and hydraulic properties; DI = Ductile Iron, MDPE = Medium Density Polyethylene, CI = Cast Iron, DE= dead end and LP=Looped network

Trunk mains and selected intervention	Flushed DMA	Max demand per capita [l/s.c]	Total customers/ Total pipe length [c/m]	Pipe numbers	Pipe material	Pipe location	Length [m]	Industry recorded internal diameter [mm]
TM-1 [Normal]	DMA-A	0.0044	0.26	A	CI lined	LP	251	152
				B	DIL	DE	100	100
				C	DIL	DE	70	100
				D	MDPE	DE	221	90
				E	MDPE	DE	166	90
TM-2 [Passive]	DMA-C	0.0044	0.21	F	MDPE	DE	93	102
				G	MDPE	DE	99	102
				H	MDPE	DE	47	102
				I	MDPE	DE	203	102
				J	MDPE	DE	94	102
TM-3 [Control]	DMA-E	0.0050	0.20	K	DIL	DE	253	80
				L	DIL	DE	343	100
				M	MDPE	DE	111	90
				N	MDPE	LP	204	90
				O	MDPE	DE	187	63

4.4.4 Fieldwork procedure and timeline

The flow conditioning trial was designed using the validated PODDS model (Husband and Boxall, 2015) to achieve max 1.0 NTU during the trial period. TM-1 and TM-2 were designed with a 40% shear increase addition to the typical historical (12 months) peak shear termed normal flow conditioning, and 16% addition to the peak shear termed passive flow conditioning. These target shear stresses were selected based on the WTW hydraulic capacity and trial point local drainage conditions. All flow conditioning trials were operated under similar conditions, i.e. same time of the day, equipment and monitoring sections to standardise the trial. Since the trunk main flow profiles were demand driven and diurnal in pattern, target excess shear stress was achieved during morning peak demand period when the network demand was highest. Morning peak demand period was chosen as it requires the lowest additional demand to achieve the target level.

To pre-set the DMA pipes to known level of cleanliness prior any flow conditioning trial, initial flushing trials were undertaken. The repeated flushing trials were undertaken after the completion of all trials to determine the impact of different material loading on accumulation rates (see trial plan in Figure 7). Previous work reported that no notable turbidity responses were observed beyond flushing at 1.12 N/m^2 (Boxall and Prince, 2006) and 1.2 N/m^2 (Husband and Boxall, 2010) shear stress and 1.5 m/s (Vreeburg, 2007) velocity for small diameter (≤150 mm) plastic pipe. Whilst the first two (shear stress) values were confirmed via fieldwork and fitted measured response to the PODDS model, velocity of 1.5 m/s was identified based on notable turbidity response compared to average typical values. Even though the methods were different, observed values were found to be similar, suggesting its universality for smooth pipes. Therefore, for this study, plastic pipes were chosen for the flushing study due to velocity to shear stress conversion is being less critical for smooth pipe compared to rough pipe e.g. unlined CI main and shear stress to achieve 1.2 N/m^2 (Husband and Boxall, 2010) or above was relatively easier for the chosen network. Both initial and repeated flushing of DMA pipes were conducted with similar conditions to the initial trial, e.g. flow rate, flow step increase, flushing duration, same time of the day and same equipment's to maintain the results consistency. Figure 9 shows a typical setup of flow conditioning and DMA flushing trial including monitoring equipment.

a) b)

Figure 9: Intervention operation with the UK specified hydrant standpipe integrated ABB Aquamaster flow meter and turbidity monitoring through twin ATI Nephnet loggers (Turbidity unit included orange boxes and black flow cell)where a) is day time flow conditioning and b) is night time DMA flushing.

4.4.5 Flow conditioning and DMA flushing data monitoring

The typical turnover time for the three trunk mains under highest flow conditioning discharge was approximately 3.5 hrs. Hence given the expected propagation effects of material mobilisation, a turbidity sampling resolution of 15 minutes was selected to provide sufficient definition of the material mobilisation response. Since the turnover time for the typical DMA pipe with average pipe length of 150m and velocity of 1.2 m/s was 2 minutes, sampling was measured at the 1Hz frequency to ensure at least 10 measured points to define temporal response. To collect flow data during flow conditioning and DMA flushing trials, an ABB Aquamaster flow meter (www.abb.com) attached to a Langham UK hydrant standard standpipe was used. The ABB flow meter used in this work measured flow with an accuracy of ±5% of reading and maximum working pressure of 12 bar. Flow and therefore shear stress were increased carefully with a gate valve connected to the standpipe discharge point. The ATI Nephnet (www.atiuk.com) instruments were used to measure turbidity responses during flow conditioning (acute loading) and DMA flushing using infrared (IR) Nephelometric measurement process. The ATI Nephnet logger functioning range was set to 0-4.0 NTU for flow conditioning trial and 0-400.0 NTU for DMA flushing period. Instruments were calibrated with formazin samples under standard laboratory conditions. Turbidity data was spot checked regularly by a 2100Q Hach handheld logger (www.hach.com) which was also calibrated with standard formazin dilution samples. The handheld turbidity meter was calibrated for 0-800.0 NTU with an accuracy of ±2% of reading. A one-off 24 hour pressure at trunk main downstream point was measured using Syrinix Transientminder (www.syrinix.com), to calibrate the pipe roughness and therefore to estimate shear stress for all three trunk mains. The pressure logger range was set for 0-20 bar with an accuracy of 0.1% of full-scale output.

4.4.6 Long-term data monitoring

Figure 7 shows the equipment used for continuous flow and turbidity measured in both the upstream and downstream section of the selected trunk main. Continuous flow and turbidity measurement from the trunk mains was conducted at a 15-minute frequency. The ABB Aquamaster flow meter at the inlet of each trunk main and DMAs were available prior to the interventions. A similar ABB flowmeter was used to check flow conditioning and flushing flows achieved. To measure the treated water turbidity, a Sigrist Aquascat 2 turbidity instrument (www.photometer.com) was available at the WTW outlet. The turbidity instrument range was set to 0-4.0 NTU with an accuracy of ±0.001 NTU using the IR Nephelometric measurement process. To determine the downstream chronic loading, continuous turbidity data were measured at the trunk main downstream initially with an ATI Nephnet instrument (www.atiuk.com) from October 2015 to February 2016. The ATI Nephnet logger functioning range was set to 0-4.0 NTU for continuous measurement with an accuracy of ±5% of reading using IR Nephelometric measurement process. After January 2016, Evoqua Hydraclam (www.evoqua.com) loggers were deployed. Like the ATI and Sigrist logger, Hydraclam used the IR Nephelometric measurement process with a range set for 0-10.0 NTU with an accuracy of ±5% reading. Spot checks were made bi-weekly using Hach handheld turbidity instruments as detailed above.

4.4.7 Data processing and analysis

Due to discolouration particles' cohesive nature (Boxall et al., 2001), it is anticipated that a drift could present in continuous turbidity data as optic lens fouling (Gaffney and Boult, 2012). To minimise the turbidity drift, the ATI Nephnet logger lens was cleaned on site bi-weekly during its deployment period (From October 2015 to February 2016), with little or no drift observed and good agreement shown with spot checks. After February 2016 the Hydraclam logger was deployed in which turbidity drift was corrected through a proprietary "Evoqua" post-processing algorithm which returned good agreement with handheld spot checks. The Sigrist logger was maintained in good order as part of the regular WTW regulatory maintenance.

The Hydraclam turbidity data had higher standard deviation (SD) of 0.38 (sample size, n≥5800) compared to the ATI Nephnet unit (SD=0.03, n≥5800). A potential reason for the lower variation with the ATI logger is that it used a continuous flow of 0.02 l/s (~1.2 l/m) for the sampling process. The Hydraclam logger used a purging system, running 6L of water at a flow rate of 0.1 l/s to waste prior to sampling each 15-minutes. While the total discharged volume (>6L) can be increased, it was limited due to the local drainage conditions. This is considered to produce additional noise in the data due to partial purging of the hydrant riser and connecting pipework. To minimise the noise from the measured signal, different rolling means were explored and 1-hour was selected based on minimising the signal noise yet retaining the measured behaviour. Figure 10 shows a moving average sensitivity study comparing measured turbidity response of treated water and the three trunk mains. It is noted that turbidity responses produced during the flow conditioning trial were not included in the smoothing process as the higher flows through the hydrant negated the riser turnover effect.

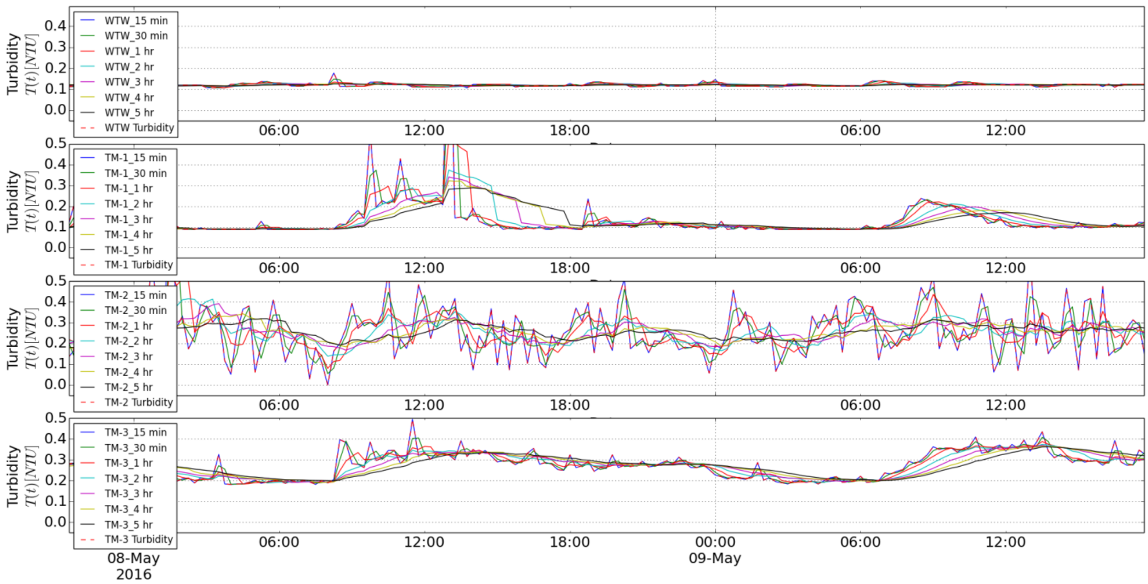


Figure 10: Moving average sensitivity analysis of measured turbidity responses where 1 hour is chosen as suitable conditions. Data is limited to 0-0.5 NTU for better visibility

Due to operational constraints, the applied shear stresses were not consistent with both pipes and hydraulic events, and therefore volumetric turbidity responses (flow and turbidity) were not directly comparable. Hence the flow conditioning trial results were assessed and compared via a material release rate. To compare the responses with a single measurable unit, measured flow and turbidity response was calculated by integrating the turbidity time series with the volume of water used and dividing by the sum of the imposed excess shear stress and calibrated pipe effective wall area. This is as shown in equation 1

$$Material\ release\ rate\ per\ excess\ shear\ stress\ \ per\ unit\ area = \frac{\int_0^t T_{ds}(t).Q(t)dt}{\frac{\pi}{4}D^2\int_0^t \tau(t)} \quad (1)$$

Where T_{ds} is the turbidity in NTU, t is the trial duration in seconds, Q is the volume of water in m^3/s, τ is the applied excess shear during the trial period in N/m^2, and D is the internal pipe diameter in m. The excess shear stress was determined by average daily shear stress minus the additional shear stress imposed during the trial period. The imposed shear stress was calculated using equation 2.

$$Applied\ shear\ stress,\ \tau = \rho g R S_0 \quad (2)$$

Where, ρ = discolouration material density in kg/m^3, g = gravitational force in m/s^2, R = hydraulic radius in m and S_0 = hydraulic gradient unit less. In this calculations, ρ and g were used at 1100 kg/m^3 (Boxall et al., 2001; Ryan et al., 2008) and 9.81 m/s^2. Hydraulic gradient was calculated for the entire pipe length using Darcy-Weisbach formula integrating Swamee-Jain Colebrook-white approximation (Swamee and Jain, 1976) and network hydraulic properties stated in table 1.

While the flow conditioning data was compared using material release rate, the same calculation was not valid for DMA pipe flushing data as the flow rate was relatively consistent for a short period of flushing durations, with no continuous change of shear stress. Hence, flushing data was compared by using volumetric material loading ($NTU.m^3$) which integrated the turbidity time series in NTUs and multiplied by flushing water volume in m^3/s. This volumetric loading calculation was done at initial flushing (time zero) and repeated flushing (+12 months) and estimated how long it would take for repeated flushing values to reach their initial volumetric loading conditions assuming a linear accumulation process (Boxall et al., 2003a; Cook and Boxall, 2011). This is as shown in equation 2:

$$Volumetric\ loading = \int_0^t T_{ds}(t).Q(t)dt \quad (2)$$

To investigate the significance of intervention impact on downstream network material accumulation rates, samples were statistically analysed by IBM SPSS v22.0 software. Due to the small sample size and assuming samples were not normally distributed, nonparametric testing was chosen to investigate the difference between the chronic and acute material loading rate with a significance level (α) of .05. For multivariate analysis, the Kruskal-Wallis H test was chosen, and Mann-Whitney U test was used for bivariate sample analysis.

4.4.8 Clustered discolouration contact analysis

Previous research showed that trunk mains have a critical influence on DMA level discolouration contacts (Cook et al., 2015) as hydraulic disturbance from trunk mains can impact on multiple connected DMAs within a short period of time. Hence, spatial and temporal clustering can differentiate customer contact induced from trunk mains from more local DMA specific contacts. Prior to clustering analyses, records of discolouration customer contacts from the downstream DMAs were collected from 2013 till 2016 including the +12 months monitoring period maintained in accordance with regulatory requirements. Customer contact data for the +12 months monitoring period were collected for assessing the impact of trunk main interventions and how this differed from DMA local induced contact compared to the previous years. Contacts were then clustered with respect to hydraulic events affecting two or more DMAs within a 24 hour rolling period; hence, data were segregated into two groups: those from upstream effects (mainly the trunk mains) and those locally within DMAs. Discolouration contact data were cross-checked with other hydraulic events (e.g. bursts or rezoning) captured by the trunk main flow meter and bursts repair report.

4.5 Results

4.5.1 Flow-Turbidity time series and intervention data assessment

Figure 11 presents the flow and turbidity profiles of the three trunk mains from October 2015 to January 2017. One major burst event affected TM-1 flow, occurring between trial 2 and trial 3. Four burst events were recorded by the TM-2 flow meter during the measured period. Two burst events were observed in TM-3 data. All these hydraulic events occured in the downstream networks except the burst event in June 2016 in TM-3 which occurred approximately 1.3 km from the WTW outlet. During the repair process, TM-3 demand was rerouted via parallel TM-2 at 1.7 km from the WTW outlet. This then initiated the burst event in TM-2 at the same time. The burst in December 2016 in TM-3 was a small event that caused 6 l/s additional flow and was located approximately 2.0 km from the WTW outlet. However, no observable turbidity response was found from the bursts event. This is potentially for the bursts upstream initiated location, no material propagation was recorded.

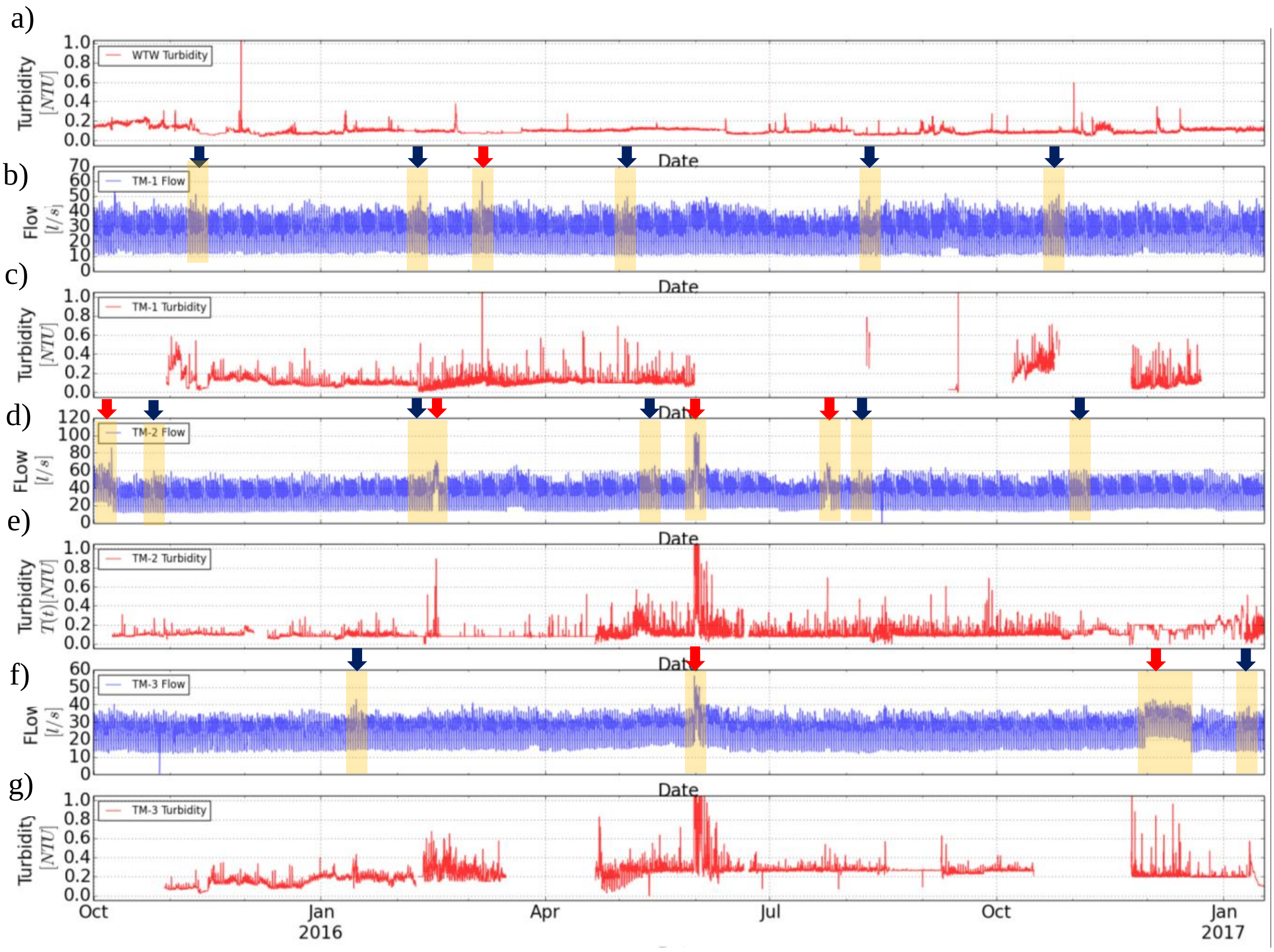


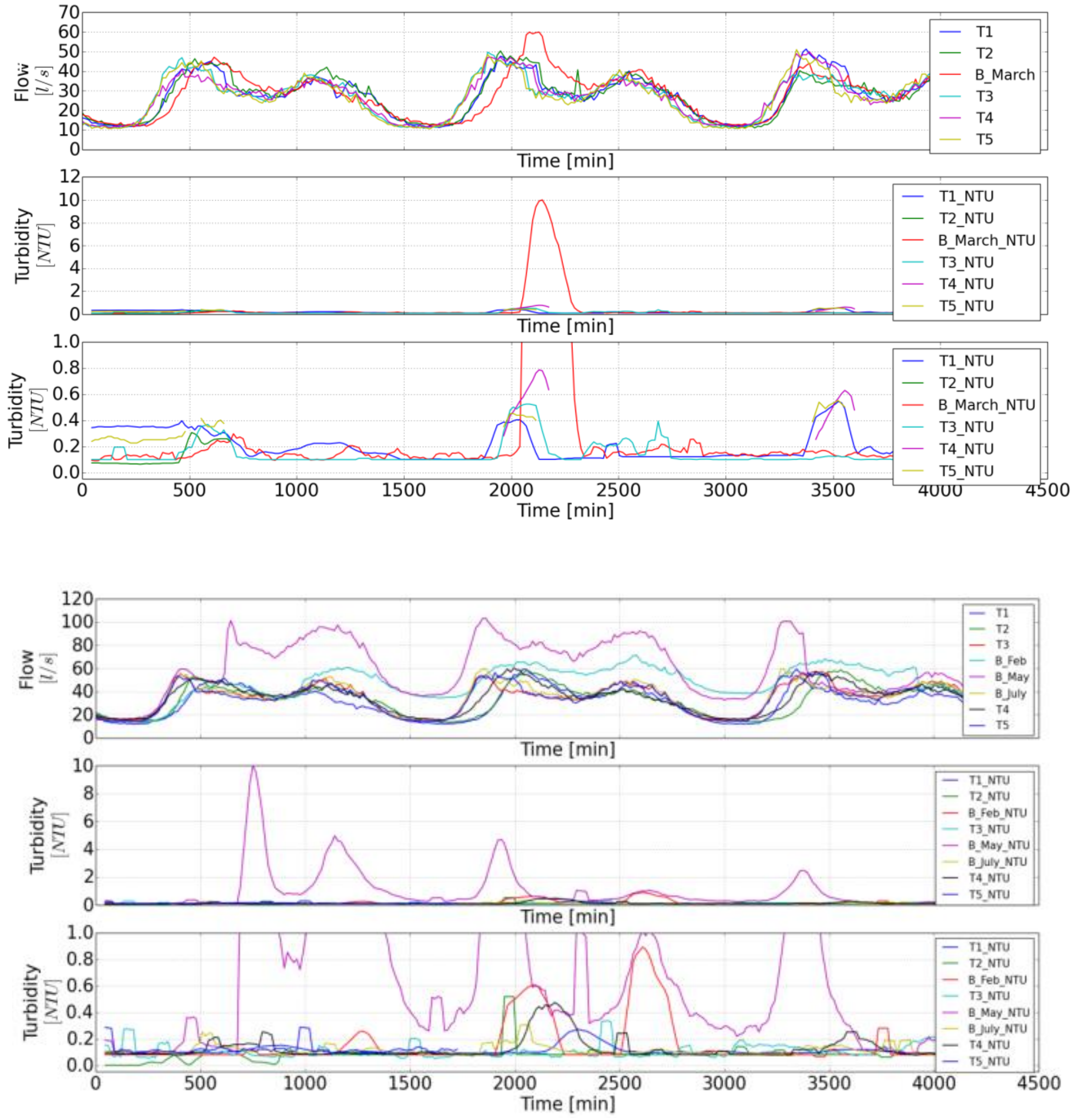
Figure 11: Flow and turbidity profiles of treated water and three trunk mains from October 2015 till January 2017. Redline is turbidity in NTU; blue line is flow profile in l/s. The dark blue arrows indicate the flow conditioning trials, and the red arrows are the burst events with:. a) Treated water turbidity, b) TM-1 flow, c) TM-1 turbidity, d) TM-2 flow, e) TM-2 turbidity, f) TM-3 flow and g)TM-3 turbidity.

Figure 12 presents the three trunk main flow conditioning and bursts event measured flow and turbidity responses obtained by setting zero minutes at midnight (12:00 am) of starting day for each event, continuing for a period of up to 72 hours (three days) and overlaying those events' data to compare results. A three day continuous data period was chosen as each trial was required to achieve continuing target shear stresses up to a maximum of 72 hours. The TM-1 data in Figure 12(a) show that a notable amount (≤1.0 NTU) of material was mobilised from all planned trials, with turbidity observed from each daily shear stress increase. Even though the imposed shear stress was similar for all planned trials, similar strength material was mobilised from each of those successive trials. A peak turbidity of about 10.0 NTU was recorded during the burst in March 2016. While relatively stronger strength material was released from the burst in March 2016, enough material was accumulated within the two months period to have observable response from trial 3 (≤0.5 NTU).

Figure 12(b) presents TM-2 flow conditioning and burst event induced flow and turbidity data. No notable turbidity was observed from any TM-2 flow conditioning trials, potentially affected by multiple burst events during the monitoring period. However, material was released from each burst event under varying imposed shear stress conditions. For TM-3, only trial 1 and the burst in May 2016 had observable turbidity responses, as shown in Figure 12(c). In all three trunk mains cases, these events were separated by some period that allowed material to accumulate and discolouration responses from the imposed hydraulic condition from each event, suggesting that the same strength material accumulated or returned on the pipe wall..

a)

b)



c)

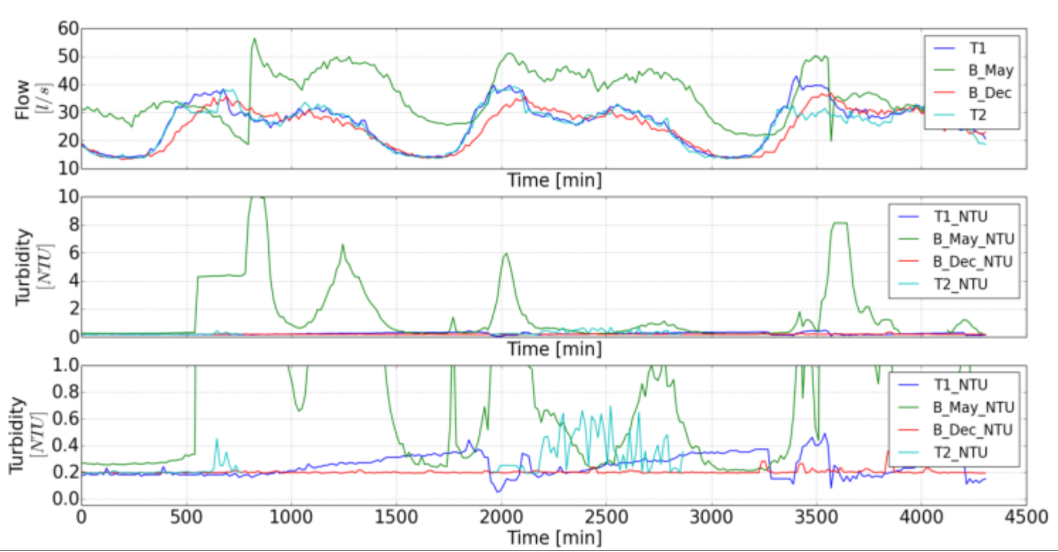


Figure 12: Flow conditioning and bursts event flow and turbidity responses for the three trunk mains where time zero started from trial start day at 12 am (midnight) up to 72 hours where a) TM-1, b) TM-2 and c) TM-3. Here T represents flow conditioning trial and B represents bursts. Top plot: Flow profile in l/s, middle and bottom plot: showing trunk main downstream measured turbidity where bottom plot is limited to 0-1.0 NTU for better visibility

Figure 13 presents the flow conditioning trial and burst events induced responses as material release rate per unit excess shear stress per unit wall area with focus both on bursts events (left Figure) and flow conditioning events (right Figure). It is evident from Figure 13(a) that the release rate value of TM-1 was lowest in trial 2 and 3 and the highest value was recorded during trial 5. Since similar imposed shear was implemented for all trials in TM-1, it was expected that similar amounts of material would be mobilised, which was not observed. However, during bursts in February 2016, the material release rate was 19230 NTUm^3/N which potentially impacts on the trial 3 results as the lower values compared to the other period evident from Figure 13(a). Figure 13(b) shows that relatively less material was mobilised from TM-2 (passive flow conditioning) compared to TM-1, which was anticipated due to the lower imposed shear stress conditions. A high amount of material was released from multiple TM-2 burst events and that may impact on the following flow conditioning event, e.g. trials 3 and 4 of TM-2. Figure 13(c) shows that similar amounts of material were released from two planned trials from the control main (TM-3) with 12 months interval. Similar to TM-2, TM-3 bursts in May, 2016 also released high amounts of material with potential impact on the trial 2 responses. However, due to the long interval period between the bursts in May, 2016 and trial 2, it is difficult to quantify the impact. The TM-3 burst in December, 2016 was calculated for 48 hours of monitoring as there was no observable response measured from this event. It is to be noted that most material was released from TM-1 and TM-3 compared to TM-2 trial.

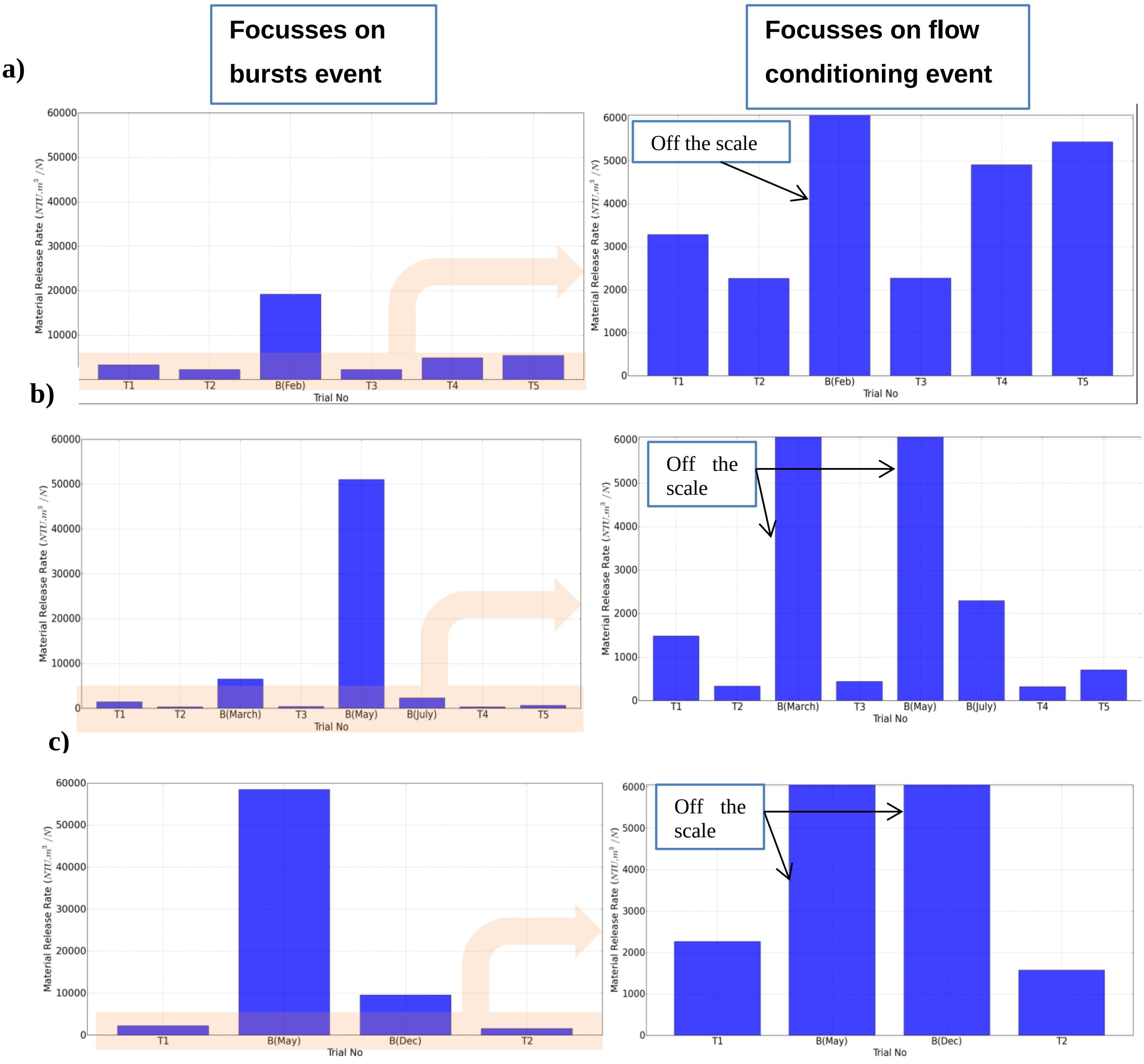


Figure 13: Material release rate per unit excess shear stress per unit wall area (NTU.m^3/N) of flow conditioning trial and burst events where T stands for flow conditioning trial and B stands for bursts. a) TM-1, b) TM-2 and c) TM-3. Left plot y-axis is limited to 0-60000 NTUm^3/N to focuses on bursts data and right plot is limited to 0-6000 NTUm^3/N to show flow conditioning data properly. It is to be noted that x-axis are different for each trunk main data.

4.5.2 Trunk main long-term turbidity response comparisons

Figure 14 illustrates the continuous measured turbidity profile of the treated water and downstream ends of the three trunk mains for visual assessment for the month of May, 2016. This monthly data period was chosen for turbidity comparisons as it was just after the trial 3 of TM-1 and TM-2, before the May 2016 burst event in TM-2 and TM-3, and approximately in the middle of the investigation period when all loggers were recording continuous data simultaneously. Visual comparison of WTW outlet turbidity with each trunk main’s time series data demonstrates that additional turbidity particles were produced while water was transported through the trunk mains; this is particularly evident in TM-3 data. The observed turbidity signals typically exhibited a diurnal pattern, suggesting an impact from the diurnal variations in flow..

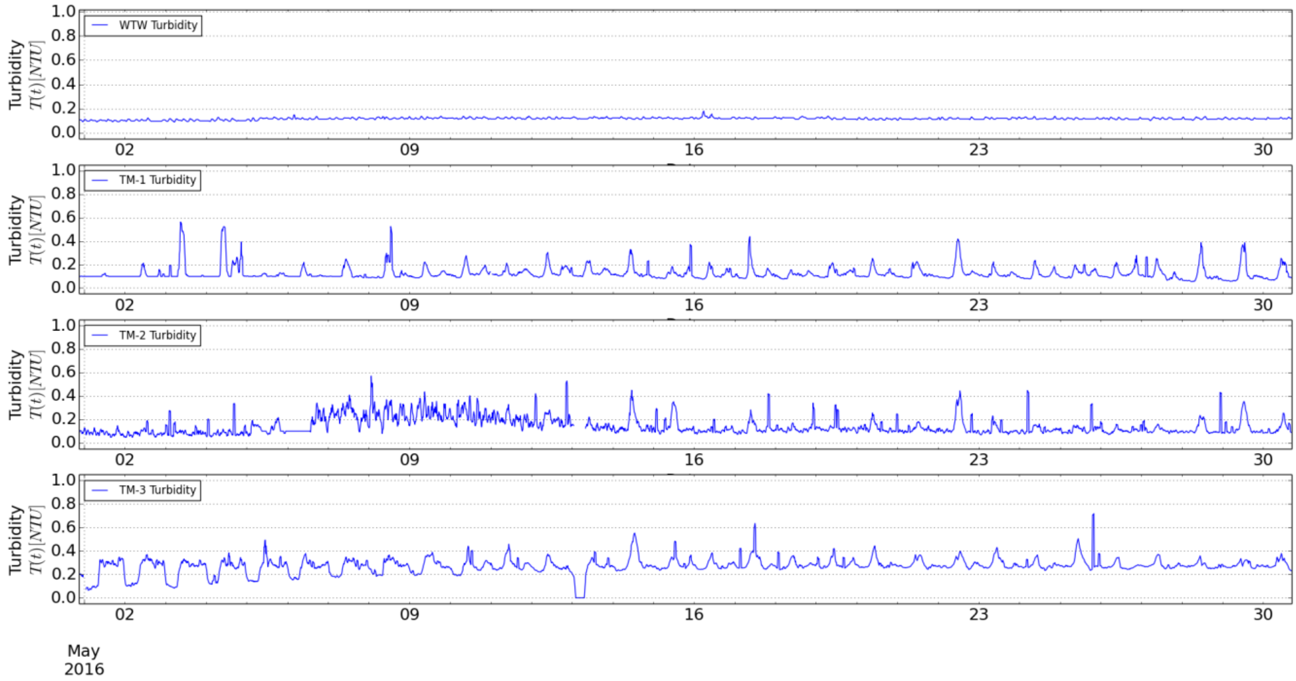


Figure 14: Long-term measured upstream-downstream turbidity response of May 2016 (sample size, n≥2950) where the top plot shows WTW treated water and the remaining three bottom graphs show the three trunk mains’ downstream responses. All data are limited to 0-1.0 NTU in y-axis scale for better visibility

Figure 15 shows the histogram assessment of turbidity frequency ranging from 0 to 1.05 NTU for each trunk main. Long-term results demonstrate that higher frequency of low turbidity response (0-0.15 NTU) is mostly found in treated water following TM-2 and TM-1. However, a relatively higher number of turbidity responses were recorded for TM-3, suggesting higher chronic loading transporting from TM-3 compared to other trunk mains.

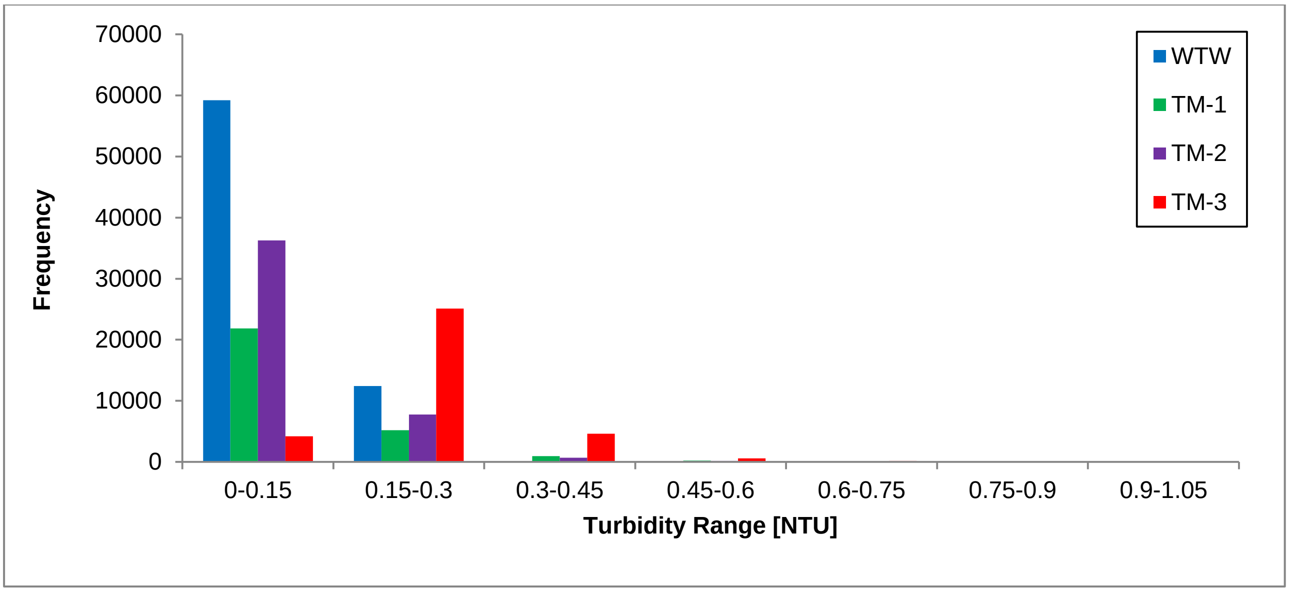


Figure 15: Histogram analysis of WTW and the three trunk mains turbidity responses (sample size n≥25000). Histogram is limited to 0.-1.05 NTU in x-axis. Measured data collected from October 2015 to December 2016..

To assess how bulk water turbidity varied during the transit and to quantify the hydraulic events' impact on turbidity responses, continuous measured turbidity data of treated water and the three trunk mains were processed in box-whisker plots as shown in Figure 16. Box-whisker plots were processed in a monthly duration from October 2015 till December 2016 showing the median, 25th, 75th and 99th percentile range of data. Figure 16(a) shows that treated water median turbidity lies between 0.07 and 0.15 NTU with no abrupt variations, suggesting low turbid water supplied in trunk mains. TM-1 (normal flow conditioning) measured data show that additional particles were generated compared to treated water responses as shown in Figure 16(b). The initial turbidity response of TM-1 (October, 2015) was relatively higher than WTW responses. It is apparent from Figure 16(b) that median turbidity response was improved after the flow conditioning trial started from November, 2015 and after that median turbidity was relatively nearer to the WTW baseline, suggesting that the flow conditioning influences turbidity behaviour. The only exception was observed in October, 2016, where relatively higher turbidity responses were measured than in the other months. This could be related to the change from European summer to autumn cyclic seasonal loading, although, TM-2 did not show a similar response. However, following trial 5 (implemented at the end of October, 2016), notable improvement of turbidity was observed from October (median=0.27 NTU) to November (median=0.075 NTU) and December (median=0.10 NTU). Similar to the TM-1 monthly turbidity response, Figure 16(c) shows that the TM-2 (passive flow conditioning) median response was nearer to the treated water response, suggesting the improved turbidity conditions were due to the periodic flow conditioning and bursts events. . It is evident from Figure 16(c) that following the bursts in May, 2016 median turbidity was improved. Figure 16(d) presents that the control (TM-3) network monthly turbidity response was increased over time, suggesting that following trial 1, turbidity responses degraded due to no maintenance conditions. No immediate impact on turbidity response was observed from the bursts in May, 2016; however, a little improvement was measured from July 2016 onwards, with a slight improvement after the December, 2016 bursts event. The improvement of turbidity after hydraulic events, e.g. bursts and flow conditioning and increased turbidity response due to no maintenance conditions, suggests that cleaning interventions have impact on bulk water turbidity behaviour.

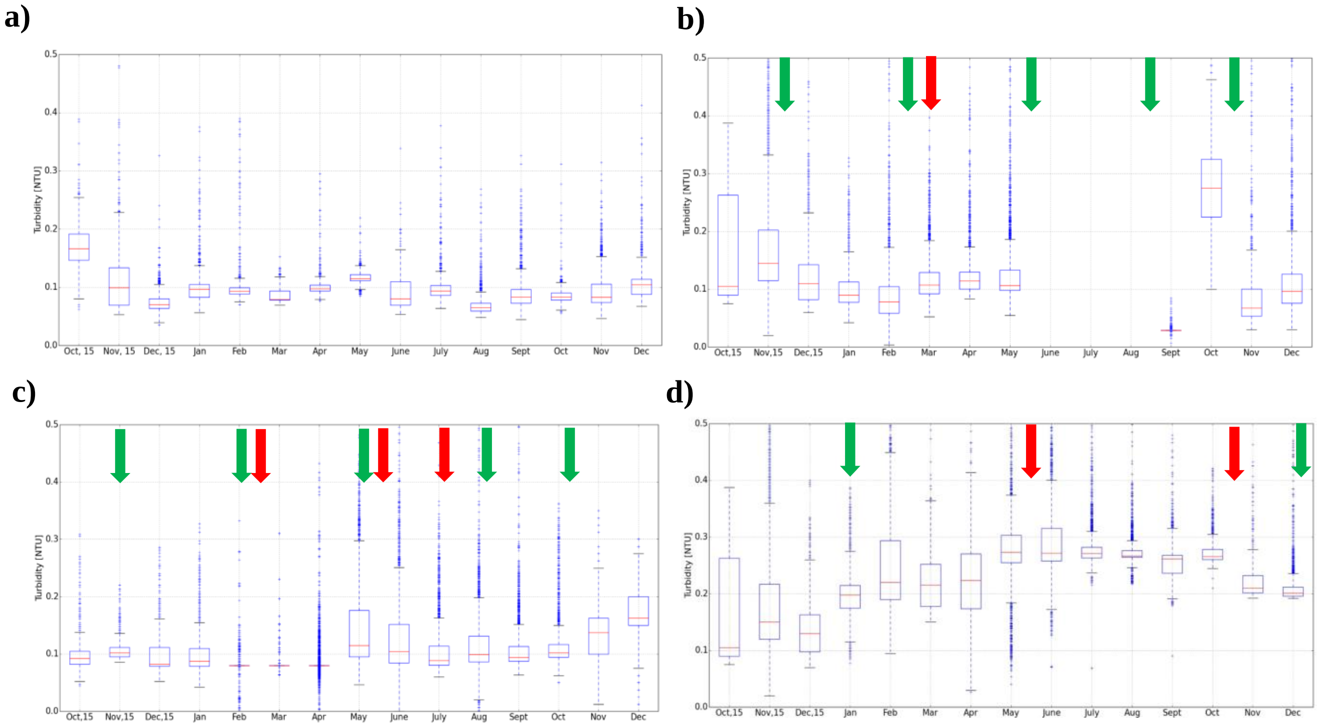


Figure 16: Monthly variations of treated water and the three trunk mains' bulk water turbidity responses in statistical box-whisker plot: a) Treated water (sample size, n≥40000), b) TM-1 (normal flow conditioning, n≥25000), c) TM-2 (passive flow conditioning, n≥38000) and d) TM-3 (control, n≥33000). Data processed from October, 2015 till December, 2016 show the range, median, max-min data containing 99th percentile with 0-0.5 NTU in y-axis scale, highlighting both planned (flow conditioning) and unplanned (burst event). Here, green arrows represent flow conditioning trials and red arrows burst events. Turbidity data from the duration of the flow conditioning trials and burst events were excluded from the box-whisker analysis. X-axis timeline extended from October 2015 till December 2016.

Figure 17 presents the +12 months turbidity responses comparisons between treated water and the three trunk mains summarised in a box-whisker plot. The upstream turbidity response or WTW baseline for +12 months lies between 0.08 and 0.15 NTU with a median of 0.115 NTU. Amongst the three trunk mains, TM-2 had the lowest response, with a median of 0.11 NTU which was closer to the treated water values. TM-1 measured data were a little higher than TM-2 and the median was about 0.135 NTU, yet nearer to the treated water exiting values. The maximum turbidity response was recorded for TM-3, with median about 0.275 NTU which was about 240% higher than leaving water response and about 200% higher than TM-1 and TM-2. The results show that in comparison to the control main, chronic turbidity loading from the trunk mains (TM-1 and TM-2) was improved due to the periodic flow conditioning intervention.

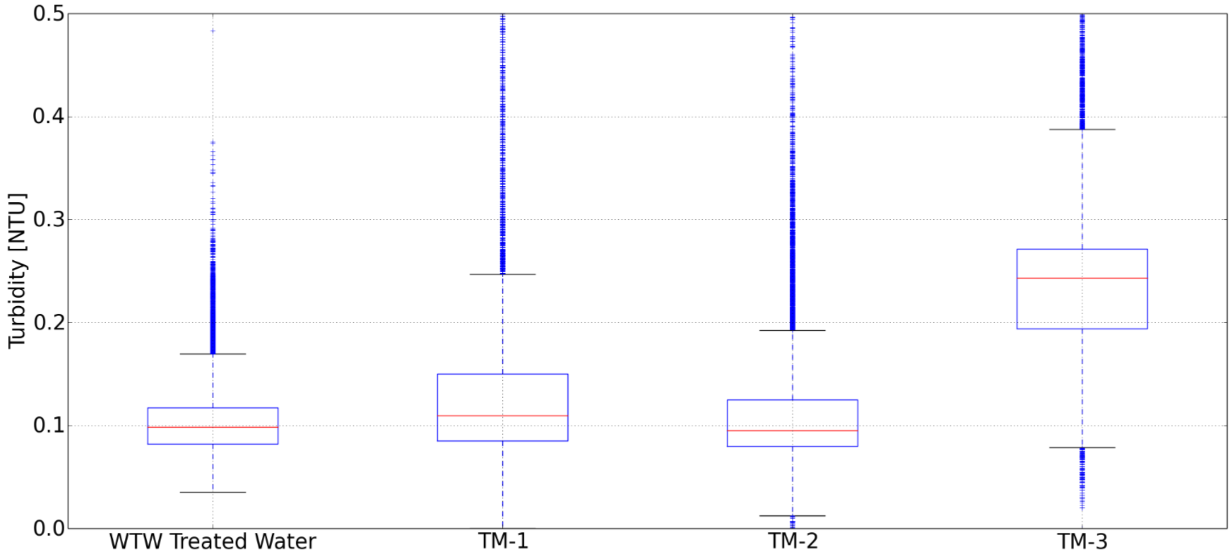


Figure 17: Statistical box-whisker plot for measured turbidity data (sample size, n≥25000) of upstream treated water and downstream trunk mains of total monitoring period showing the range, median, max-min data containing 99th percentile and y-axis limited to 0-0.5 NTU. TM-1 is Normal flow conditioning, TM-2 is Passive flow conditioning, and TM-3 is the control trunk main

4.5.3 DMA flushing results

Figure 18 shows initial and repeat flushing turbidity data along with the stepwise demand increase used to produce target shear stress (>1.2 N/m^2) for two example pipes from two separate DMAs. Figure 18 data were chosen randomly from the flushing trials, with all other flushing results observed to be similar. The graph demonstrates that each stepwise increase in imposed flow (and therefore shear stress and velocity) caused material release from the pipe wall. Figure 18 also demonstrates that initial flushing of the previously undisturbed pipes produced more turbidity than the repeated flush, indicating the cohesive layers had not fully regenerated after +12 months. Figure 18 shows mobilisation of material with each increase in shear stress, confirming that the accumulation of material occurs across a range of strengths. It is to be noted that peak turbidity from TM-3 flushed pipe was higher than from TM-1 pipe suggesting a higher amount of material accumulated in control main fed DMAs.

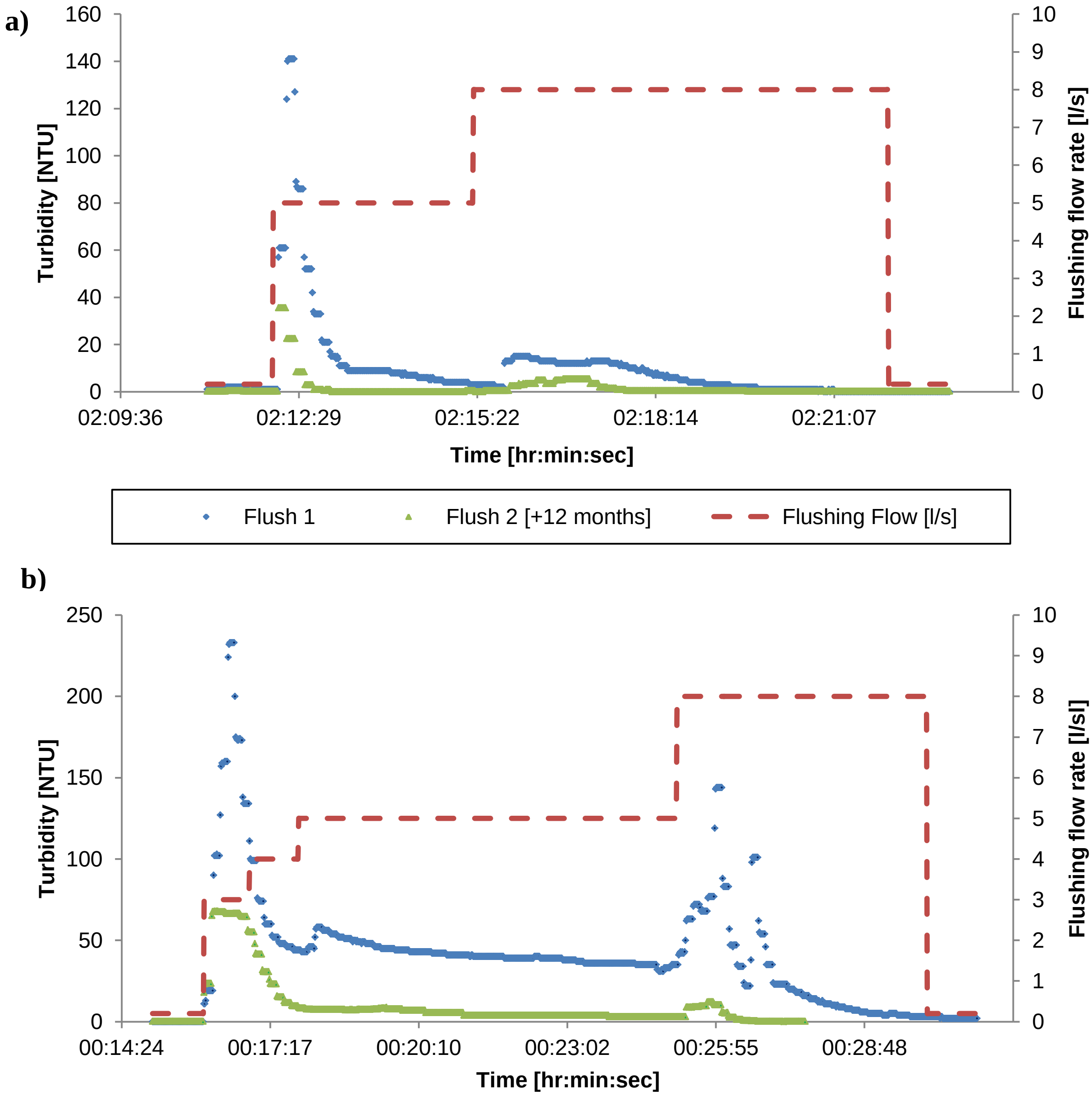


Figure 18: Randomly selected DMA pipes repeated flushing trial at time zero and 12 months of investigation a) TM-1 pipe E where D=90mm and L=166m b) TM-3 pipe M where D=90 mm and L=204 m

Table 4 presents the DMA pipes repeated flushing data with their average accumulation return period after 12 months and time taken to reach initial volumetric loading via mass-balance analysis. It is to be noted that initial flushing condition was assumed to be the maximum discolouration risk as it was in undisturbed conditions. DMA-A (TM-1, normal flow conditioning) pipes repeated flushing results show that the average time to reach initial condition would be 2.7 years, with 2.5 years for DMA-B

(TM-2, passive flow conditioning) pipes and 2.0 years for DMA-C (TM-3, control) pipe. These assessments showed that the pipes in the DMA fed by the flow conditioning main had approximately 25% improved accumulation return period.

The Kruskal-Wallis (K-W) H test demonstrated that there was a statistically significant difference in the DMA pipes accumulation return period between all three test groups with $X^2 = 8.398$, $p = .015$. A similar statistical difference in downstream accumulation return period was found between the control group and normal flow conditioning group using Mann–Whitney (M-W) U test (U=.15, $p = .016$). However, for DMA pipes supplied from two flow conditioned trunk mains, the accumulation return period did not differ significantly according to the M-W U test (U=6.5, $p = .22$). These statistical significance tests suggests that there was no negative effect on downstream accumulation return period from the acute loading of quarterly flow conditioning intervention. Rather it seems that the reduced chronic loading due to the periodic flow conditioning intervention evident in Figures 15 and 17 has a beneficial effect on downstream discolouration risk.

Table 4: DMA flushing volumetric turbidity results and relative accumulation rate for the selected pipes. Here, DE = dead end and LP = Looped

Trunk main Intervention and DMAs	Pipe material	Pipe Location	Volumetric turbidity NTU.m^3 [1*10^5]		Material accumulation after 12 months (%)	Initial flush condition or predicted accumulation rate [year]	Statistical Significance (Kruskal Wallis H Test)
			Pre [Initial]	Post [+12 months]			
DMA-A (Normal flow conditioning, TM-1)	CI lined	LP	8.3	3.8	46	2.1	X^2 =8.398 P= .015
	DIL	DE	7.3	1.9	27	3.7	
	DIL	DE	3.1	1.3	42	2.4	
	MDPE	DE	4.2	1.5	35	2.8	
	MDPE	DE	3.1	1.3	41	2.4	
DMA-C (Passive flow conditioning, TM-2)	MDPE	DE	3.3	1.5	45	2.2	
	MDPE	DE	8.9	3.3	37	2.7	
	MDPE	DE	1.3	0.5	39	2.5	
	MDPE	DE	1.5	0.5	30	3.3	
	MDPE	DE	6.6	3.6	55	1.8	
DMA-E (Control main, TM-3)	DIL	DE	2.1	1.0	47	2.1	
	DIL	DE	12.2	7.9	65	1.5	
	MDPE	DE	0.53	0.23	55	2.3	
	*MDPE	*LP	*2.7	-	-	-	
	MDPE	DE	0.56	0.26	46	2.2	

* Due to the local pipe specific burst event with no impact on overall trunk main flow, material accumulation rate could be influenced and hence not valid for comparison.

4.5.4 Discolouration contact assessment

In order to further evaluate the downstream network performance due to the different trunk main interventions and resulting downstream loading, long-term discolouration customer contact data were assessed for two or more DMAs (for detail see Figure 7 network schematics). Due to confidentiality issues it is not possible to publish actual contact numbers. To aid this, un-clustered or total discolouration customer contact was presented as contact numbers per 1000 properties as shown in Figure 19. The un-clustered discolouration contacts data were collected from 2013 to 2016, including the +12 months monitoring duration to explore the net effect of the trunk main interventions. The recorded data depicted in Figure 19 indicate that TM-1 (normal flow conditioning) supplied DMAs contacts were increasing during the 2013 to 2015 pre-trial period, potentially due to the lack of cleaning program, and reduced after commencement of the normal flow conditioning intervention. Discolouration contacts were similar in TM-2 from 2013 and 2014, with an increase in the 2015 pre-trial period likely due to the multiple recorded burst events, mostly at DMA level. However, slightly higher numbers were recorded during the +12 month monitoring period, predominantly caused by the May 2016 burst event. It is evident from Figure 17 that TM-3 (control) fed network discolouration contacts were higher in 2013 and reduced in the following years. An on-going old CI pipe replacement rehabilitation program could potentially have contributed to the improved condition. No notable change of customer contact was observed during the +12 months post-trial monitoring period compared to the 2015 pre-trials. Although the TM-3 test DMAs were flushed prior to the investigation, no overall improvement of customer contact numbers was recorded, suggesting that overall DMA performance did not improve.

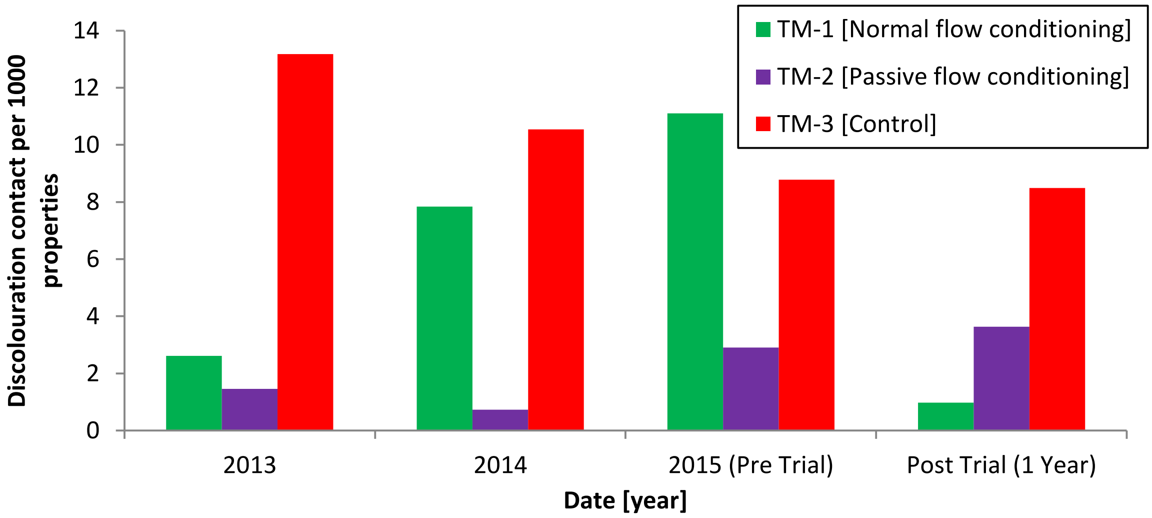


Figure 19: Discolouration customer contact data per 1000 properties for the test DMAs fed from the three trunk mains from 2013 till 2016 including +12 months monitoring period.

Following the analysis of un-clustered or total discolouration contacts from the test DMAs (Figure 17), discolouration contacts were clustered with respect to hydraulic events affecting two or more DMAs within a 24-hour rolling period. If discolouration contacts were found in more than one DMA within a 24-hour rolling period, the likely cause would be from trunk main event. Figure 20 presents the clustered contact analysis of trunk main and the percent contributed from trunk mains compared to total recorded contact. No trunk main induced contact was recorded in 2013 and few contacts during 2014, suggesting overall performance was good at that period. Although a high number of trunk main induced contacts was observed in the 2015 pre-trial period in the TM-1 fed network due to multiple bursts events, no clustered contacts were found during the monitoring period despite the TM-1 burst event in March 2016 evidencing the benefit of flow conditioning. Relatively low trunk main induced contact was observed in TM-2 fed network during 2013 and 2014, although it was higher during the 2015 pre-trial and monitoring period. Similar to TM-2, TM-3 supplied network had relatively low clustered contact in the 2013 and 2014 period and an increase was observed during the 2015 pre-trial and monitoring period. Both TM-2 and TM-3 contacts were affected by the same burst event in May 2016. About 90% of contacts in the TM-2 fed network and 65% of those in TM-3 were produced from the burst event alone in the monitoring year, suggesting that DMAs' performance of TM-2 (passive conditioning) was good compared to that of the TM-3 (control) network.

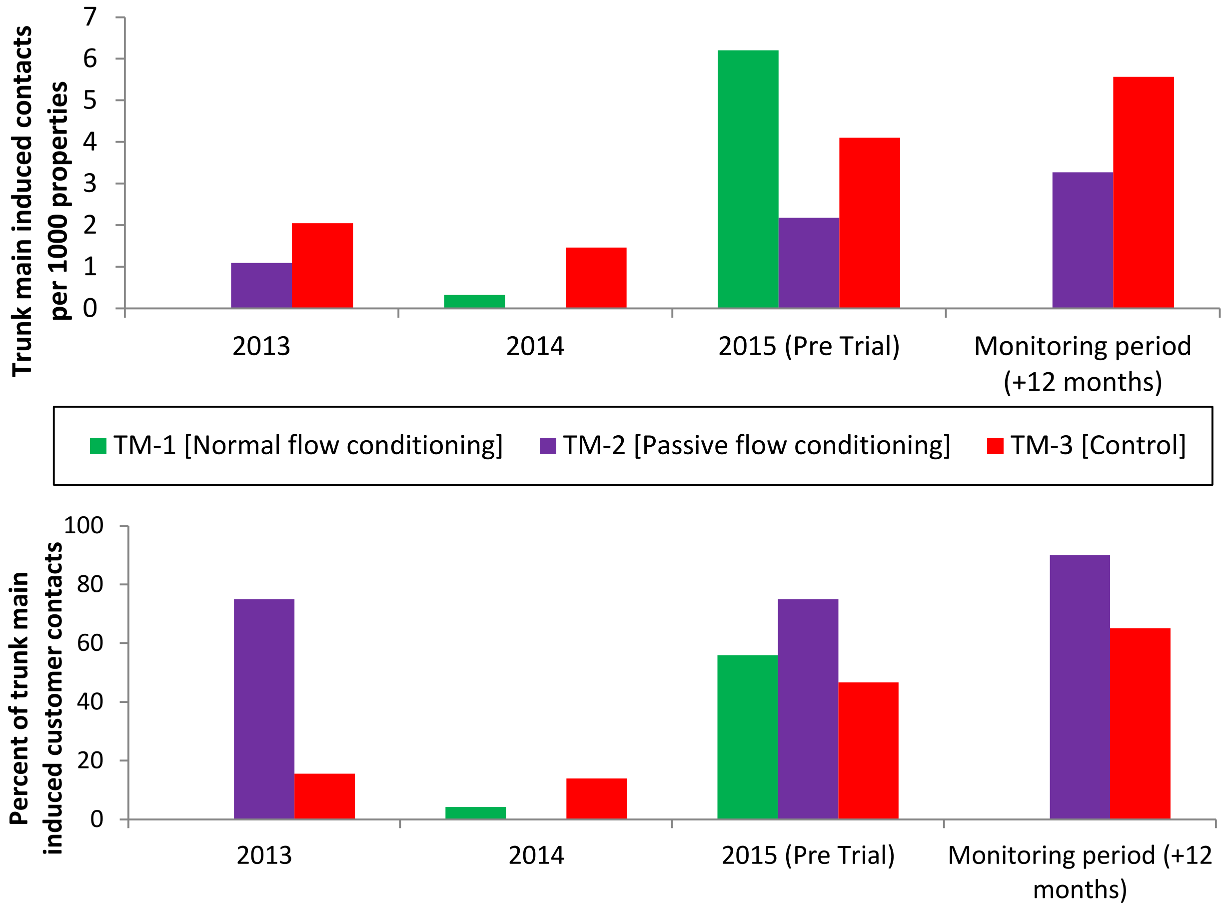


Figure 20: Clustered analysis of the trunk main induced customer contact data a) trunk main contact per 1000 properties and b) percent trunk main contact compared to un-clustered contact

4.6 Discussion

4.6.1 Trunk main turbidity time-series data and diurnal profile

Intensive +12 months upstream and downstream turbidity measurement showed that in all trunk mains water quality deteriorated with increased turbidity concentration compared to the treated water. This evidences the concept of water quality deteriorating during transit due to the physicochemical and microbiological interactions. The measured higher turbidity could have been produced from varying sources, i.e. iron corrosion as test mains were unlined CI (Carriere et al., 2005; Sarin et al., 2002, 2003), chemical reactions (Kirmeyer, 2000; Sly et al., 1990) and biological growth (LeChevallier et al., 1987; Gauthier et al., 2001; Meckes, 2001). However, this study did not investigate each variable’s influence on this degradation process separately. Diurnal turbidity profiles showed that hydraulics influence the daily mass flux, with material accumulating during night time low flows and mobilised during the morning peak, as shown in Figure 14. This field evidence of diurnal turbidity response suggests that a continuous daily material mobilisation-accumulation process cycle exists in the distribution systems. Similar turbidity correlation to diurnal flow pattern was also observed by Cook, (2007) and Machell and Boxall, (2014). Mounce et al. (2015) used the semblance technique to correlate long-term continuous measured flow and turbidity data and suggested that as the correlation gets stronger, the risk increases, indicating that material is well accumulated on the pipe wall and poses higher risk. The diurnal turbidity behaviour was more apparent in TM-3 (control) main (Figure 14) compared to the other two flow conditioned mains, suggesting potentially higher discolouration risk from non-intervention networks.

4.6.2 Material mobilisation and accumulation processes

The trunk main flow conditioning trials (Figure 12) and DMA flushing data (Figure 18) showed that each step of the shear stress increase mobilised additional turbidity, confirming that materials have cohesive strength properties whereby weak layers mobilise earlier than the stronger ones. This pattern of discolouration is supported by several previous studies (Boxall et al., 2003b; Cook and Boxall, 2011; Husband and Boxall, 2011, 2016). Material release rate assessment in Figure 13 demonstrates that material accumulated continuously, supporting the previous work of Boxall et al. (2003b) and Cook and Boxall (2011).

The periodic hydraulic intervention both at trunk main and DMAs demonstrated an increase in material being mobilised during each trial with similar shear stress step up to the initial trial, suggesting that material regenerated across the range of shear strength simultaneously (see Figure 12 and 16). If it were regenerated from strong to weak layers as reverse of the mobilisation process, following the initial trial, material should have mobilised with small increase of shear stress and hence no responses would have been observed from repeated higher imposed shear stress conditions. However, this was not observed from repeated trials and bursts condition (Figure 12 and 18). While the previous works observed this accumulation behaviour for small diameter pipe both at controlled laboratory (Sharpe, 2012) and operational conditions (Husband and Boxall, 2011; Husband et al., 2010), this work demonstrates for the first time that material accumulates across all strengths simultaneously in the large diameter pipe systems. This improved understanding of accumulation processes for trunk mains is critical to understand how risk returns on the pipe wall and for designing discolouration management strategy by managing the cohesive layer strength and imposing controlled hydraulic intervention pro-actively.

4.6.3 Shear stress impact on continuous turbidity profiles

During the experimental design, it was conceptualised that all three trunk mains had similar physical, chemical and biological chemistry as each had similar hydraulics properties, pipe material and fed from the same source. The implication is that prior to any intervention, the three trunk mains had similar bulk water and wall conditions, and turbidity responses should have varied due to the different imposed shear stress conditions. Overall long-term turbidity assessment (Figure 17) shows that background turbidity was improved due to the periodic flow conditioning interventions compared to the no intervention system. Although reduced turbidity in bulk water due to hydraulic intervention contradicts the findings of Gaffney and Boult (2012), Mounce et al. (2015) evidenced that turbidity events frequency improved after flushing. While both studies had used the same dataset, results can vary subject to analysis and interpretation. This improvement in chronic loading conditions can be explained using Figure 21 which shows that during normal operations without any hydraulic disturbances, cohesive layers are in an equilibrium state with current hydraulics (Boxall et al., 2001) and a continuous daily material mobilisation-accumulation process cycle exists (Husband and Boxall, 2011), as shown in Figure 14. However, the net material balance in equilibrium conditions remains the same as the layer reaches its maximum accumulation capacity under normal operating conditions. Typically weaker cohesive layers are mobilised during the flow conditioning event and to maintain the equilibrium over time, additional particles from bulk water can accumulate on the remaining layer. However, in normal operation, this effect does not take place as there is little or no capacity left on the cohesive layers. As a result, particles generated from complex reactions between bulk water and pipe wall during transit remain suspended for normal operations, and the net response makes a greater contribution to chronic loading. This finding is observed in the monitoring data (Figure 17) where background turbidly was lower in the flow conditioning mains compared to the control main.

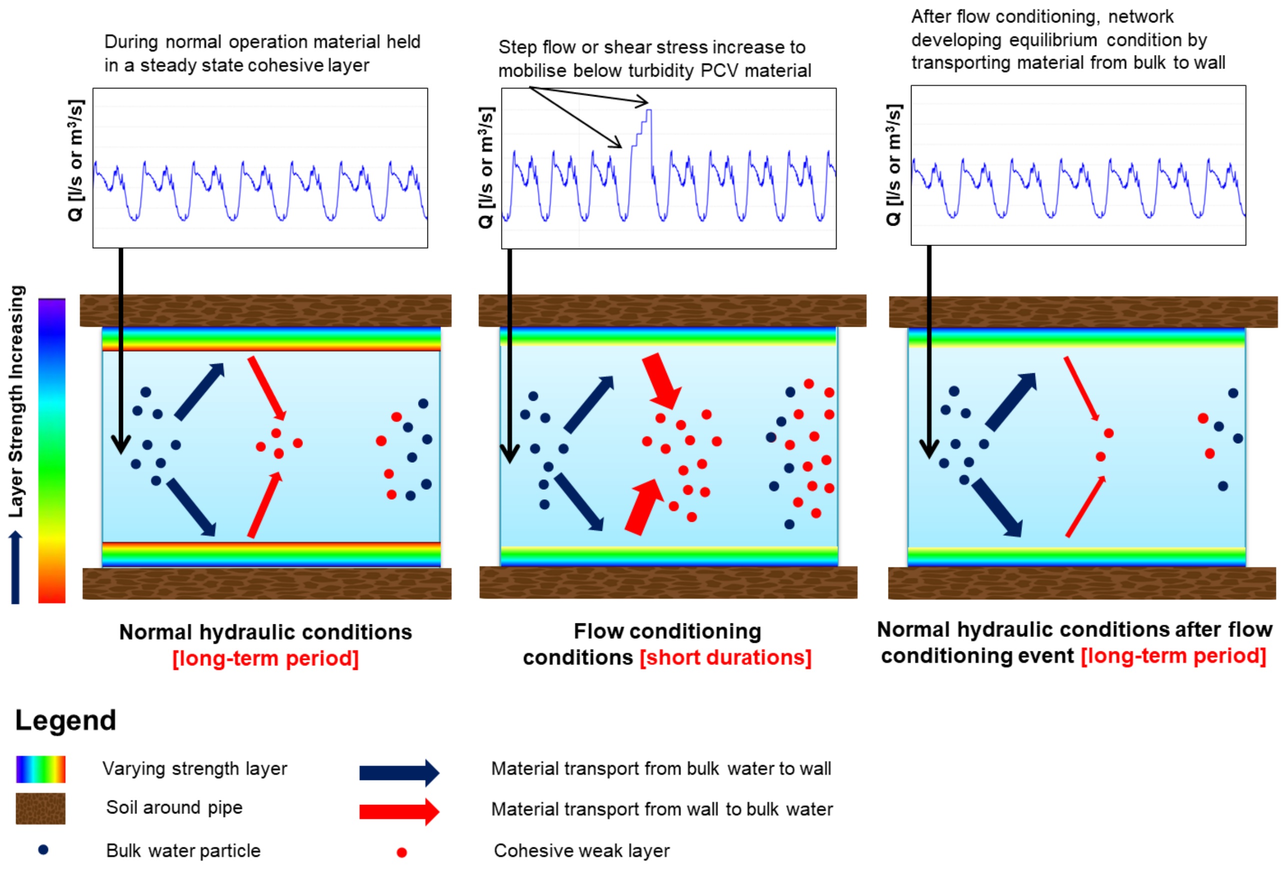


Figure 21: Influence of hydraulic behaviour on material mobilisation-accumulation and bulk water turbidity loading response for trunk main. During normal operation (first image), partial weak cohesive layers contribute to the chronic loading continually with additional generated particles from corrosion and microbial reactions; however, the reverse process does not necessarily occur due to the steady-state layer conditions and hence increasing background chronic loading. During the flow conditioning exercise (second image), weak layers are removed and therefore cohesive layers capacity increases for additional weak layers. During long-term normal hydraulic conditions following the flow conditioning exercise (third image), bulk water particles create equilibrium cohesive layer conditions by filling the weak strength layers and hence reducing overall chronic loading.

4.6.4 Acute and chronic material loading effects

Prior to the investigation, a research concern arose that immediate acute loading from trunk mains can increase the discolouration risk compared to chronic loading. While occasional acute material loading (in this case ≤1.0 NTU for flow conditioning trial) was supplied from flow conditioned trunk mains during conditioning trial, relatively higher chronic loading from the control main was observed. Results assessed from downstream pipes material accumulation return interval (table 4) and selected DMAs discolouration contacts per 1000 properties (Figure 19 and 20) showed that downstream network performance is better with trunk mains undergoing flow conditioning intervention. Accumulation return periods are significantly lower in the control main fed downstream network, hence there is higher discolouration risk than the flow conditioned trunk mains. This is due to flow conditioning reducing the trunk main water quality degradation (turbidity responses) compared to the normal operation, and thereby reducing chronic turbidity loading in the bulk water that is continuously supplying the downstream network (Figure 17). This suggests that the higher chronic material influx from the upstream control network increases material loading on the downstream network and relatively fast build-up of material on the pipe wall. Acute material supplied from the trunk main may accumulate on the downstream pipe wall. It is also possible that acute loading simultaneously passed through the customer tap during the flow conditioning trial and was not accumulating on downstream pipe walls and hence overall pipe wall accumulation was lower for the flow conditioned trunk main. Since the 1.0 NTU target during flow conditioning main is lower than the aesthetically visible turbidity limit (4.0 NTU), it is difficult to provide conclusive evidence either that acute loading accumulates or passes through the tap. However, accumulation return period assessment suggested that pipe supplied from higher chronic loading (control main) has a lower accumulation period (higher discolouration risk) than the flow conditioned trunk main.

The increase in accumulation rates from higher turbid bulk water and vice-versa shows the significance of bulk water effect on accumulation rates and that improving treated water quality can reduce discolouration risk in both trunk main and downstream distribution zone by lengthening return periods between the cleaning interventions. A similar conclusion was drawn by Vreeburg et al., (2008). While Vreeburg et al., (2008) came to this conclusion by changing the water quality, this study evidences the significance of bulk water on discolouration risk by imposing different planned interventions. This improved understanding of discolouration risk management opens up the opportunity to assess the synergy between treated water improvement and cleaning intervention return period. Such assessment can be undertaken by analysing the trade-off between cost of improved treatment and cost of intervention such that most suitable discolouration management conditions can be designed considering from WTW to downstream network approach.

4.7 Conclusions

This study has assessed the long-term discolouration impacts of trunk main flow conditioning interventions on the trunk mains themselves and the associated downstream networks. Specific findings are:

- Chronic material loading from bulk water is more significant in terms of downstream network accumulation rate and hence discolouration risk than the occasional acute loading from flow conditioning interventions. This study provides further evidence that accumulation rates are a function of long-term bulk water quality and improving water quality can play an important role in reducing discolouration risk by prolonging the process and hence extending the periods between cleaning interventions.

- Long-term turbidity behaviour in trunk mains can be managed with repeated flow conditioning intervention whilst relatively higher chronic loading was observed from no intervention networks and hence higher risk for the whole investigated period, with some monthly variability.

- Discolouration risk in downstream networks is reduced with repeated flow conditioning. While downstream networks may get occasional acute loading from flow conditioning, reduction of chronic loading from trunk mains reduces accumulation rates or return period.

- Further evidence on material accumulation indicates that it returns at all strengths simultaneously on both large and small diameter pipes, suggesting its long-term typical nature in drinking water networks. Understanding the significance of accumulation processes can help to understand how risk is formed within the network and manage those layers proactively by implementing flow conditioning strategically.

- The finding that flow conditioning intervention provides effective discolouration risk reduction in trunk mains without creating an adverse effect on discolouration risk in the trunk main itself and downstream network highlights its value as a cost-effective way to manage long-term discolouration risk in the drinking water distribution systems.

5. Discolouration Risk Management and Chlorine Wall Decay

Reproduced from **Sunny, I.,** Husband, P.S., Moore, G., Drake, N., Mckenzie, K., and Boxall, J.B. (2017). Discolouration Risk and Chlorine Wall., CCWI 2017 proceedings, (Sheffield, UK: Figshare) doi: 10.15131/shef.data.5364475.v1

Declaration

Chapter five is a conference proceeding published in CCWI, 2017 conference. This chapter has been published under the open access Creative Commons 3.0 License. The contribution of the main author and co-authors are following:

1. **Iftekhar Zaman Sunny** is the PhD candidate and 1st author and major contributor to this published chapter. As a part of his PhD research, he has formulated the aims, developed the methodology, monitored and analysed necessary data and outlined conclusions for this published paper. Primarily he has designed and written the chapter having inputs from the co-authors as stated in point 2.

2. **Prof. Joby Boxall and Dr. Stewart Husband** are the primary academic co-authors of these chapters. They have supervised the PhD research project and provided critical input into the research methodology. They have helped to define and refine the aims, overall structure of the thesis, interpretation of results and formulation of discussion points. They also have provided necessary guidance on the chapter content and structure including grammar corrections and correcting sentence structure in order to clarify the sentence meaning.

3. The other three co-authors are **Graeme Moore, Nick Drake and Kevan Mckenzie** from Scottish Water who has supported this PhD project by providing necessary network access, data provision and equipment facilities.

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1st author	2nd author	3rd author

Mr. Nick Drake	Mr. Kevan Mckenzie	Prof. Joby Boxall
4th author	5th author	Last author

5.1 Abstract

This paper explores the concept that periodic imposed excess shear stress events to manage discolouration risk in trunk mains can also impact on the chlorine wall decay by changing the properties of the accumulated pipe wall material. By implementing a series of varying magnitude shear stress events in multiple trunk main demonstrated that significant material was mobilised, thereby cleaning the mains and reducing discolouration risk. Measured chlorine data also suggests that repeated shear stress intervention reduced the chlorine wall decay relative to a control network and the larger the intervention greater the benefit. Calibrated first order chlorine decay simulations in EPANET supported this finding. The modelling results further show that the wall decay has a dominant influence on this change even for these large diameter pipes. The significance of these findings is to evidence the additional value of regular hydraulics based cleaning interventions for large diameter mains delivering service improvement in terms of both discolouration risk and persistence of chlorine residual.

Keywords: Discolouration risk, shear stress, chlorine decay

5.2 Background

5.2.1 Discolouration processes and management strategies

The effective management of water distribution networks from water treatment works (WTW) to tap approach is an essential action to safeguard public health and asset longevity. However as soon as water flows through distribution systems, it starts to deteriorate due to complex physico-chemical and microbiological interactions. Hence, water quality failure is predictable considering network complexities and the diverse variables interacting with bulk water and pipe wall. This includes discolouration incident due to the mobilisation of accumulated material from the pipe wall. Discolouration is a wide-spread water quality issue due to its visibility and causes the highest consumer contacts globally which affecting customer confidence in tap water (Vreeburg and Boxall, 2007). In 2001, the PODDS (Prediction of Discolouration in Distribution Systems) model (Boxall and Saul, 2005) was developed and validated to describe the behaviour of the wall bound accumulated layers and hence to simulate discolouration response. The model assumes accumulated layers have cohesive strength properties where layers conditioned by the peak daily shear stress, can be mobilised during excess imposed shear stress conditions. Discolouration due to the hydraulic disturbance is critical for transmission (trunk) mains as it can cause a substantial impact on large numbers of downstream consumers. However, interventions to remove wall bound materials from large diameter pipes are often complex, expensive and potentially disruptive for consumers. Based on the PODDS model concept of conditioning layers with excess imposed shear stress, a non-invasive flow conditioning strategy (Husband and Boxall, 2015) was developed by the University of Sheffield in collaboration with UK water companies. This strategy involves periodic interventions to impose excess shear stress in such a way to mobilise controlled amounts of material, below the UK turbidity regulatory limit of 4.0 NTU. This method is designed to be implemented in operational networks without interrupting customer supply. This strategy has been successfully implemented in several trunk main systems (Cook et al., 2015; Husband et al., 2011b).

5.2.2 Chlorine applications and decay processes

To limit biofilm regrowth and to protect against microbial contamination, application of free chlorine is widely used in the water distribution systems. However, during transit chlorine concertation is reduced due to the reaction with numerous bulk water and pipe wall constituents. Loss of chlorine within distribution system mainly occurs in two processes: a) bulk decay (k_b): is the 1st order exponential reaction coefficient and reacts with bulk water organic and inorganic constituents and b) wall decay (k_w): chlorine reacts with pipe wall biofilms, accumulated materials and corrosion scale (Al-Jasser, 2007). Previous research has shown a strong correlation of bulk decay with initial chlorine concentration, total organic carbon and temperature (Hallam et al., 2003; Powell et al., 2000) where the typical values found between 0.024 -17.7 (Speight and Boxall, 2015). Typically wall decay is site specific and can only be determined through a calibration process. Several studies reported that chlorine decay increases with the rise of Reynold numbers (Menaia et al., 2003; Ramos et al., 2009), although no investigations are examining how the properties of accumulated material influences the chlorine decay in an operational distribution system.

5.2.3 Discolouration risk and microbial affiliation

Typically discolouration is considered to be an inorganic particulate issue, although substantial percentage of organic content has indicated microbial affiliation (Gauthier et al., 1999). Recent studies suggested that biofilm may play a vital role for discolouration process (Husband et al., 2016) which is considered to hold floating inorganic-organic particles and creates a robust protected environment for microorganism against the impact of disinfection (Cowle et al., 2014). Similar to accumulated material cohesive nature, biofilms have been identified as a cohesive, three-dimensional polymer structure that can be mobilised with increases in shear stress (Abe et al., 2012). Research indicates that chlorine penetration is limited into the biofilm matrix and have a reduced efficacy against biofilm microorganisms (Chen and Stewart, 1996; De Beer et al., 1994). Therefore by mobilising the top weak biofilm layer along with cohesive material layer during shear stress events potentially expose fresh biofilms which is a concern that it could increase the chlorine wall decay due to the new wall condition. While the flow conditioning has been proven to be good for controlling discolouration risk, the aim is to explore if it has any impact on chlorine wall decay.

This paper investigates the long-term impact of periodic flow conditioning intervention on chlorine wall decay. The robustness of the chlorine wall decay coefficient assessment was tested by long-term data monitoring and modelling in multiple similar operational trunk main system.

5.3 Methods and materials

5.3.1 Site details

To investigate the impact of trunk main flow conditioning on chlorine wall decay, a UK-based operational water distributional network was selected. The network was chosen to have three trunk mains fed from a single water source and hence the same chlorine residual and bulk water properties from WTW inlet. Single water source also ensured similar water chemistry existed in the trunk mains. All three trunk mains had similar hydraulic behaviour and pipe material and as a result similar discolouration risk prior to the investigation. These conditions also ensured similar decay processes as chlorine decay is influenced by both hydraulic conditions and pipe material. Table 5 presents the three selected trunk main hydraulic conditions and pipe properties. The source water was treated with a ferric coagulation based processes. Typical chlorine dosing in the treated water varied between 1.0-

2.0 mg/l. Average treated water turbidity was between 0.05-0.2 NTU. Long-term spot samples results showed that average treated water iron, manganese and aluminium concentrations were 23, 6 and 39 mg/l. Long-term average TOC (total organic carbon) and pH was 1.7 mg/l and 8.8. A schematic representation of the selected network and its associated monitoring instrumentation is presented in Figure 22. Continuous loggers were strategically deployed to captures all the essential information for chlorine decay modelling assessment.

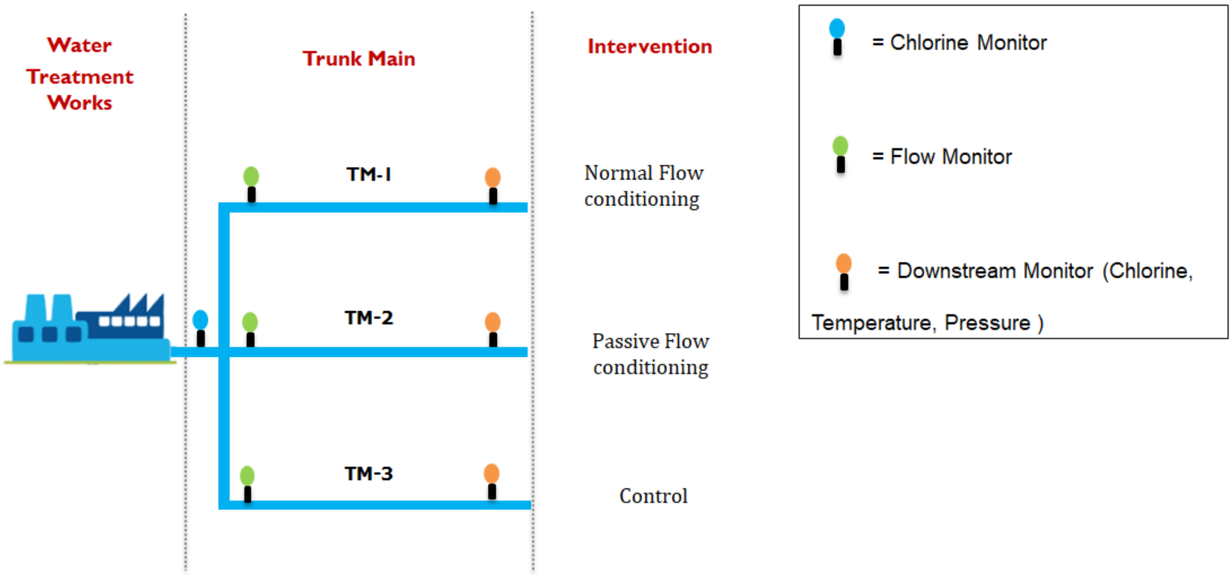


Figure 22: Network schematics showing instrumentation location

Table 5: Trunk mains hydraulic properties (here CI = Cast iron)

Trunk main system	Industry recorded mean internal diameter [mm]	Pipe material	Length from WTW outlet to downstream logger [km]	Velocity [m/s] (min, average, max)	Shear stress [N/m^2] (min, average, max)	Reynold number [-] * 10^4 (min, average, max)
TM 1	304.8	Partially lined CI	6.4	0.4,0.6, 0.8	0.1,1.0,2.5	4,8,15
TM 2	406.8	Unlined CI	5.6	0.1,0.3,0.45	0.1,0.75,1.7	4,8,14
TM 3	304.8	Unlined CI	5.9	0.2,0.4,0.6	0.15,1.0,2.2	5,9,13.5

5.3.2 Fieldwork setup, monitoring and data processing

To investigate the impact of flow conditioning on chlorine decay, three independent strategies were implemented in the three selected trunk mains. Two cleaning strategies were designed, one with a 40% shear stress increase in addition to the peak shear, termed normal flow conditioning. The second with a 15% addition to the peak shear, termed passive flow conditioning. Both normal and passive flow conditioning was implemented quarterly. The third trunk main, acting as a control had a flow conditioning intervention at time zero and after 12 months. All flow conditioning trials were operated using similar conditions e.g. same equipment's and conducted at similar times of the day.

Flow, and therefore shear stress, was increased during flow conditioning intervention and measured through Langham UK specified hydrant standpipe attached with ABB magflow meter. Flow was controlled via throttle gate valve. Turbidity response during the interventions was monitored through ATI Nephnet loggers at 15 minutes frequency. Continuous flow at the inlet of the trunk main was measured by ABB flowmeter at 15 minutes sampling frequency. Free chlorine residual was measured with 15 minutes sampling interval at trunk main upstream and downstream using Evoqua Chloroclams. Continuous chlorine loggers were spot checked and calibrated with Hach handheld colorimeter. The handheld logger was calibrated against standard gel for instrument verification.

Regular discrete samples were used to measure the average treated water temperature throughout the investigated period. A one-off period of downstream pressure monitoring was undertaken for the three trunk mains using Syrinix Transientminder at 15-minute sampling frequency for hydraulic calibration purposes. Zero leakage was considered for modelling purpose.

5.3.3 Chlorine decay modelling

Prior to the chlorine residual modelling, hydraulic models were calibrated to determine a unique solution to headloss and velocity and travel times. The calibration was facilitated by using a 1 mm roughness (k_s) equal to 2 mm effective diameter (D) reduction concept (Boxall et al., 2004). The unique paired (k_s and D) values were determined from using the PEST (Doherty, 2005) calibration model integrated to EPANET (Rossman, 2000) hydraulic model. Table 6 presents the investigated trunk mains optimised hydraulic configuration.

Table 6: *Investigated trunk mains optimised hydraulic configuration*

Trunk main system	**Length [km]**	**Optimised diameter, D [mm]**	**Optimised roughness, k_s [mm]**
TM- 1	6.4	303.2	8.50
TM-2	5.5	395.8	10.35
TM- 3	5.9	292.3	7.50

The chlorine quality modelling was simulated through standard Epanet software with simplified first order reaction kinetics for decay analysis. Use was made of the functionality to separate bulk and wall decay coefficients. Prior to the monitoring, a jar test was conducted from the treatment works final water at 5(±2)°C water temperature with k_{b_5} estimated as 1.79 day^{-1}. Unfortunately, further jar tests were not conducted, so changes in the bulk coefficient over the year were not measured. However, temperature effects were accounted for. The site and time specific k_{b_5} value was used to determine k_{b_20} value from Arrhenius equation using the E/R value of 7300°C (Menaia et al., 2003). Bulk decay values were further corrected using equation 1 according to the recorded mean treated water temperature where necessary. Thus a representative common value for bulk decay that includes temperature effects was produced and used for all three trunk mains. The wall reaction coefficient was then adjusted to account for any other effects. Hence, systematic change across all three could be due to source effects, but the difference between the trunk mains would be due to the wall effects.

$$k_T = k_{20} * \theta^{(T-20)} \quad (2)$$

Where k_T = decay at any given temperature (d^{-1}); k_{20} = decay at 20°C reference temperature (d^{-1}); θ = temperature correction factor (unit less).

Pipe wall decay (k_w) was estimated through an iterative calibration process in EPANET using the field measurement and simulated values to maximise the correlation coefficient (R^2). As it was a single parameter calibration, a manual approach was chosen for the optimisation purposes.

5.4 Results

5.4.1 Flow time series and trial results

Figure 23 presents flow data from the three investigated trunk mains with the designated quarterly trial period. Over the 12 months monitoring period there were a series of burst events affecting all three trunk mains, these are also marked in Figure 23. All burst events occurred in the downstream distribution zone, except for the burst in May 2016 directly effecting both TM-2 and TM-3. This event started in TM-3 main 1.7 km from the treatment outlet, with the flow then rezoned via parallel TM-2 due to the maintenance work. Significant material was mobilised during these events which is not presented in this paper.

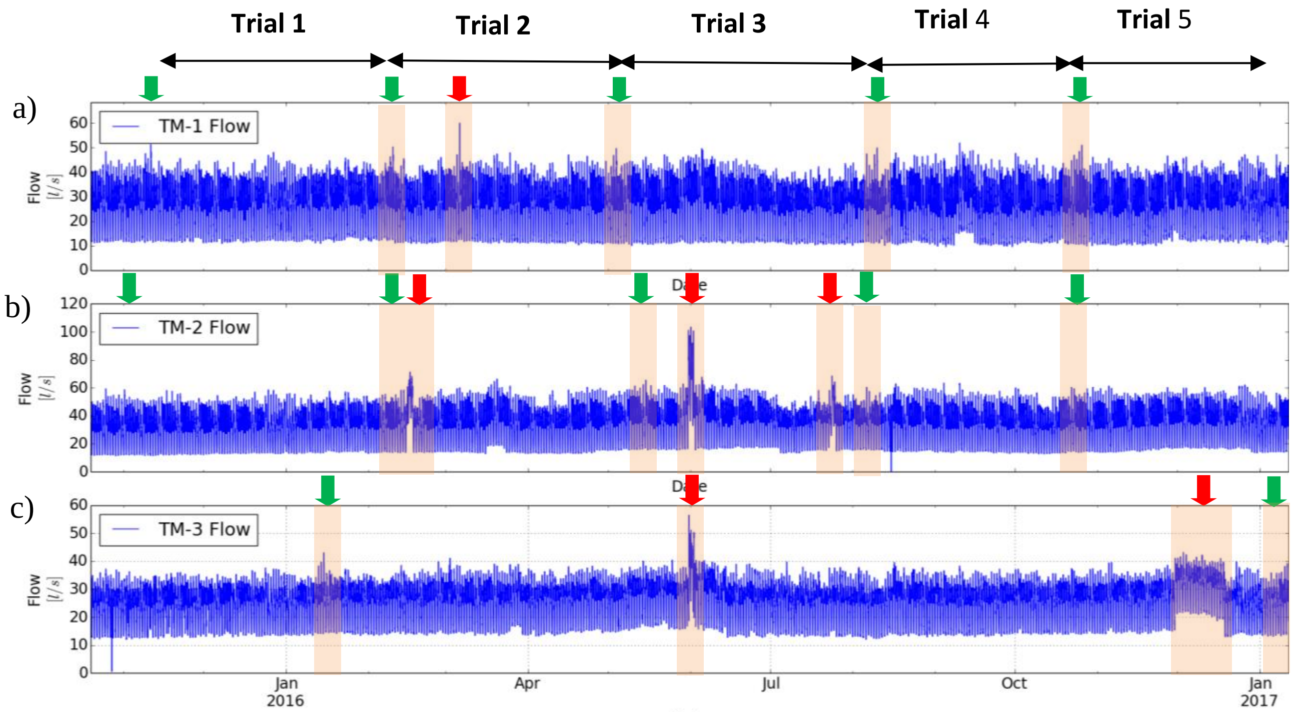


Figure 23: Flow data for the three selected trunk mains and the associated planned-unplanned event; here green arrow represent flow conditioning event and red arrow bursts event a) TM-1, b) TM-2 and c) TM-3.

Figure 24 presents the material release rate amount per unit excess shear stress during the flow conditioning trial. The material release rate was estimated by integrating the turbidity time series multiplied with flow data and divided by summed excess shear stress and effective pipe area to render a single, directly comparable number. It is evident from Figure 24 that a sufficient amount of material was mobilised from each trial, with the highest amounts recorded from the trunk main subject to normal flow conditioning. Relatively less material was released and monitored from passive flow conditioning main (TM-2) due to the multiple burst events in TM-2 which potentially affect the trial induced turbidity response. Similar amounts of material were released from the control main trials at time 0 and after 12 months, although 12 month results could have been influenced by the burst events that occurred in May and December 2016.

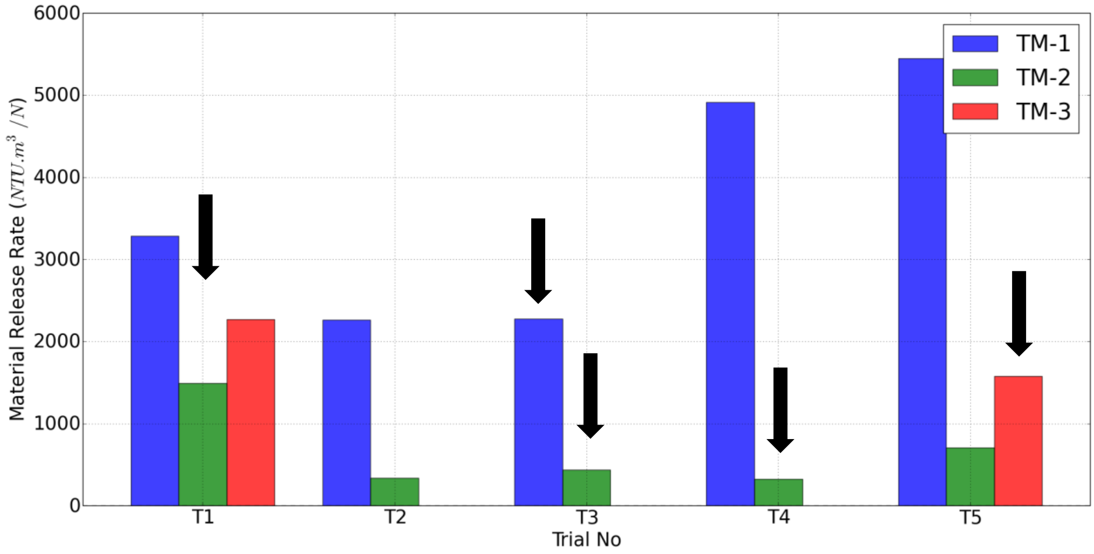


Figure 24: Material release rate per unit excess shear stress per unit wall area for all flow conditioning trial showing bursts occurrence period using black down arrows

5.4.2 Long-Term chlorine measurement

To investigate the impact of flow conditioning intervention on chlorine wall decay, modelling was undertaken to simulate the long-term chlorine measured data with an emphasis on understanding the change in wall decay coefficient. Figure 25 shows chlorine residual monitoring data from the treated water and the downstream end of each trunk main. Continuous monitoring was not functional during the first quarter following trial 1. Also, there were some periods where the instrument did not monitor data due to operational issues. The difference between WTW outlet and the downstream of all three trunk mains across the long-term data demonstrates that chlorine dissipates with time due to the reaction with water compounds and other influencing variables during transit. It is evident from Figure 25 that with the gradual rise of temperature from May 2016, chlorine dosing was increased in the treatment works to balance the downstream residual limit. Similar dosing was maintained at the WTW outlet from July to September 2016 as the temperature was steady in that period. It is also to be noted that TM-3 had relatively higher residual from mid-May to September 2016 compared to TM-1 and TM-2.

Figure 25: Time series signals of chlorine and temperature data; top plot showing treated water and 3 supplied downstream trunk mains free chlorine residual and bottom plot showing 3 trunk mains temperature profile in °C

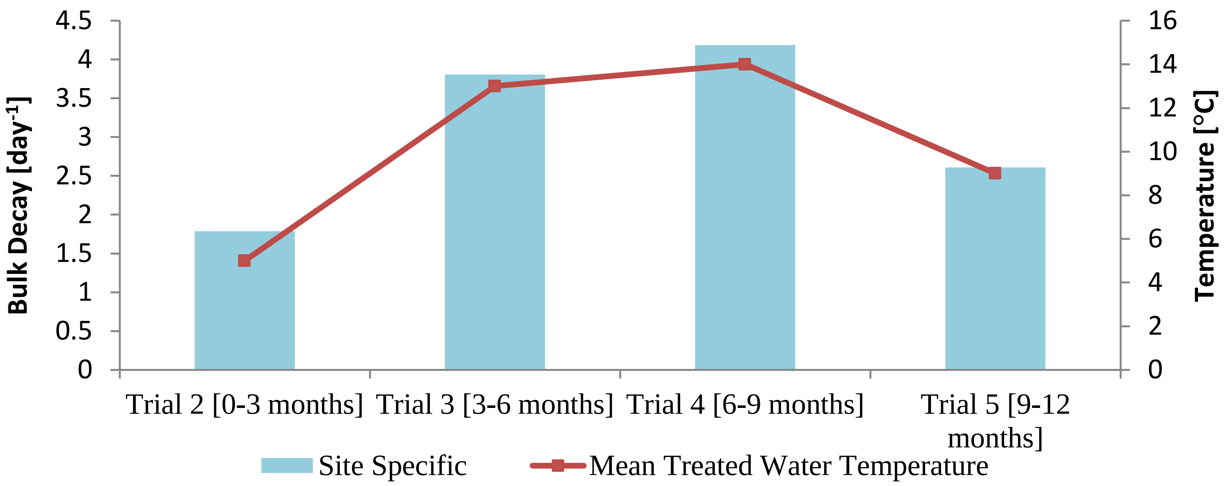
A gradual drop in downstream residual was observed during this period suggesting temperature influence on chlorine demand. After mid-September temperature started to drop steadily, yet similar upstream residual was maintained. An increase in TM-2 chlorine residual trend was observed during this period, however there was no other trunk main data available from end October to mid-December 2016. WTW chlorine dosing was lowered slowly from November due to compensate for the low water temperature. Even with relatively less chlorine dosing, downstream residual was higher indicating a strong temperature impact on downstream residual.

5.4.3 Bulk decay assessment

Figure 26(a) presents the bulk decay coefficients assessed from using a common bulk wall decay coefficient across all sites that was adjusted to the trial duration mean treated water temperature. Therefore, k_b values were adjusted with equation 2 as a similar pattern to the measured temperature profile, shown in Figure 26(a). Figure 26(b) presents the chlorine decay partial simulation for TM-1 during trial 4 to demonstrate the how wall decay influences the actual measured response of the system. Results depict that relatively large differences from downstream measured to simulated data was observed by simulating site-specific k_b value (=4.2 d^{-1}) and assuming no wall effect (k_w = 0).

This gap in simulated and measured data was compensated by adding a wall decay coefficient (k_w = 0.4) to better calibrate the model response.

a)



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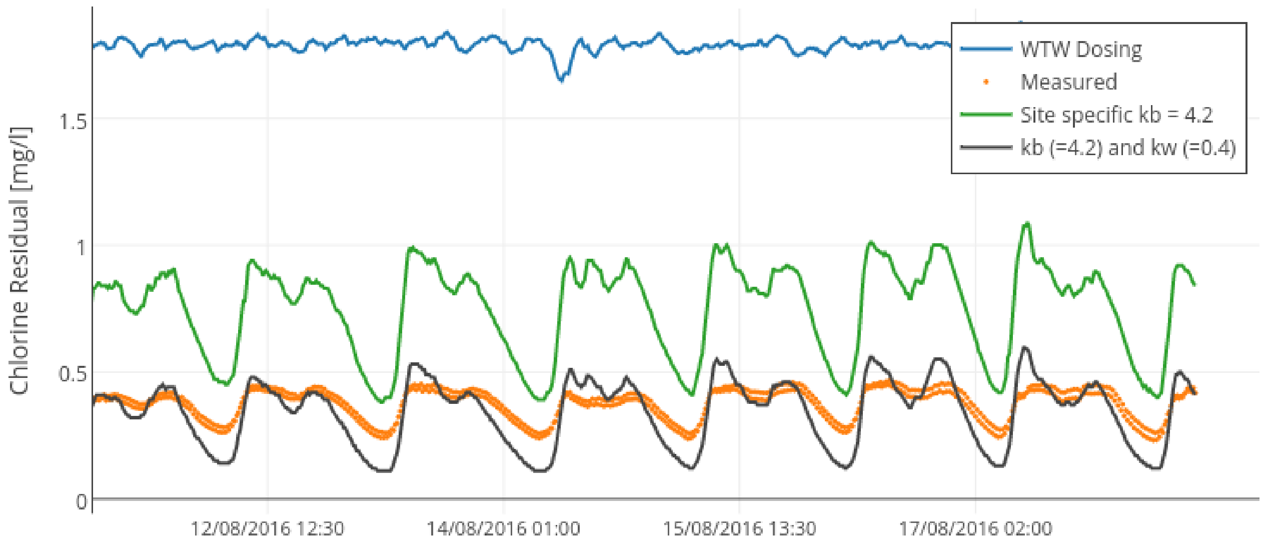

Figure 26: Bulk decay coefficient a) average treated water temperature and site specific bulk decay adjusted to the temperature, b) Upstream-downstream measured data with chlorine residual simulation using only k_b (=4.2 d^{-1}) and k_b (=4.2 d^{-1}) + k_w (=0.4 d^{-1})

5.4.4 Wall decay assessment

Figure 27 presents the calibrated wall decay for all three trunk mains simulated to the quarterly chlorine time series data. Trial 1 results were not available due to the lack of continuous chlorine data during this period. The control main (TM-3) had the highest k_w value for trial 2. A drop of k_w was observed in trial 3 for both TM-2 and TM-3, however the same trend was not observed for TM-1 suggesting the large burst event in May 2016 impacted the wall decay process. An increase of k_w was seen for TM-1 in trial 3 which is assumed to be influenced by relatively high water temperature and therefore higher microbial activities. Calibrated k_w in trial 4 was found increasing for all three cases where control main (TM-3) had the highest wall decay rate. Although the overall temperature was lower during trial 5, so does not contribute to the difference in results observed. Noticeably the control main (TM-3) k_w value, remained relatively static in trial 4 and 5 compared to the trunk mains undergoing flow conditioning. Of interest is that TM-1 performed best considering wall decay comparisons.

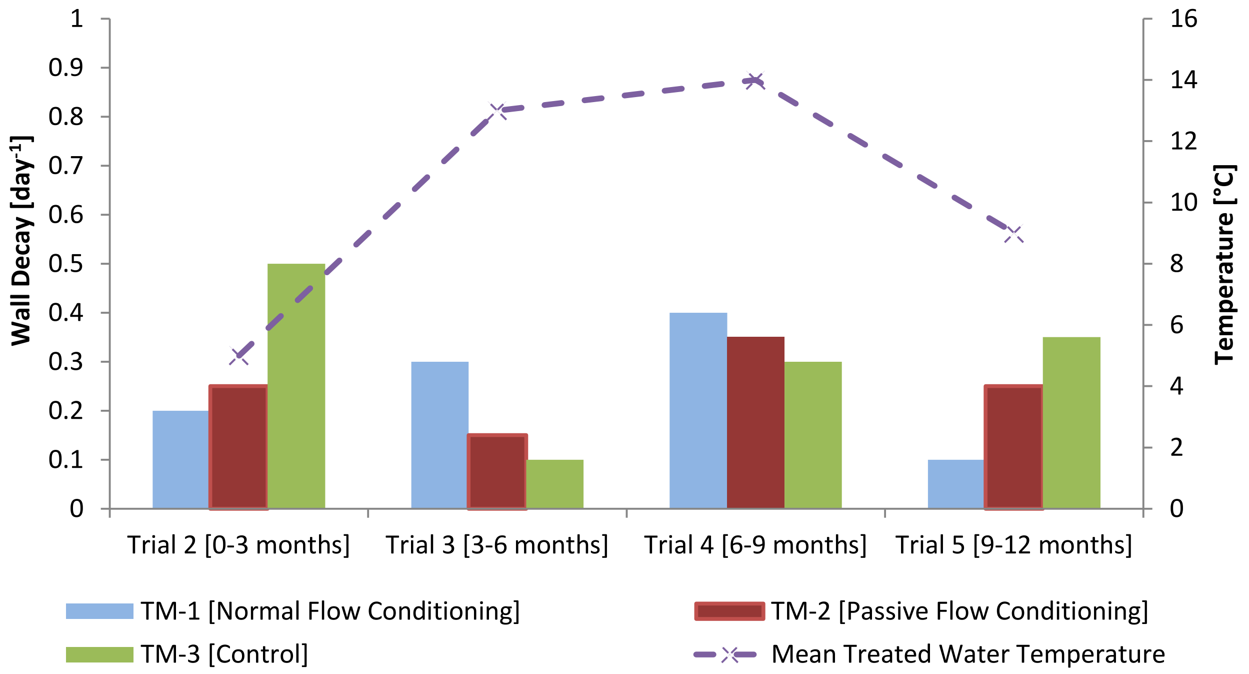

Figure 27: Calibrated wall decay coefficient for three trunk mains and mean treated water temperature

5.5 Discussions

The variation of the k_w value can be explained based on the idea that excess shear stress is generated via flow conditioning intervention or burst event mobilised discolouration material from the pipe wall as well as weak biofilm layers, potentially exposing the remaining biofilms sections to being less chlorine resistant. The available chlorine residue reacts with the reduced biofilm, which possibly inactivates faster compared to the normally developed biofilm and creates equilibrium conditions quickly. The results also demonstrated that chlorine decay has an inverse relation to the imposed shear stress, where higher applied shear could mobilise more biofilm and the remaining reduced biofilm would return quicker to an equilibrium situation. While this change in wall decay condition was observed short term between the trials, it is necessary to impose shear stress at regular intervals to manage the reduced wall decay. The implication of the findings here is that, in addition to reducing discolouration risk, long-term flow conditioning strategies could reduce chemical-operational costs by permitting lower chlorine dosing through improved maintenance of residual in trunk main system.

This study, conducted with robust monitoring and decay assessment using a simplified modelling approach, has demonstrated the positive impacts of flow conditioning on chlorine wall decay. However, further understanding is required into the linkage between chlorine demand behaviour and discolouration material present on the pipe wall such that intervention strategies can be optimised for both benefits. Further investigation should include integration of temperature into a variety of wall effects and regular bulk decay measurement.

5.6 Conclusions

This study investigated the impact of trunk main shear stress driven flow conditioning strategy on chlorine wall decay. The findings from this long-term study are:

- Periodic imposed excess shear stress events e.g. flow conditioning reduced chlorine wall decay.
- The higher the applied shear stress, the better the observed chlorine wall decay benefit.
- The improvement of chlorine wall decay due to the applied shear stress events was found to be temporary and hence regular hydraulic interventions are required to maintain the benefit.

6. Quantity and Quality Benefits of in-Service Invasive Cleaning of Trunk Mains

Reproduced from **Sunny, I.**, Husband, S., Drake, N., Mckenzie, K., and Boxall, J. (2017). Quantity and Quality Benefits of in-Service Invasive Cleaning of Trunk Mains. Drink. Water Eng. Sci. *10*, 45–52. doi: 10.5194/dwes-10-45-2017.

Declaration

Chapter six is a peer-reviewed journal paper published in the Drinking Water Engineering and Science journal as part of a special issue of CCWI 2016 conference. This peer-reviewed chapter has been published under the open access Creative Common 3.0 License. The contribution of the main author and co-authors are following:

1. **Iftekhar Zaman Sunny** is the PhD candidate and 1st author and major contributor to this published chapter. As a part of his PhD research, he has formulated the aims, developed the methodology, monitored and analysed necessary data and outlined conclusions for this published article. Primarily he has designed and written the chapter having inputs from the co-authors as stated in point 2.

2. **Prof. Joby Boxall and Dr. Stewart Husband** are the primary academic co-authors of these chapters. They have supervised the PhD research project and provided critical input into the research methodology. They have helped to define and refine the aims, overall structure of the thesis, interpretation of results and formulation of discussion points. They also have provided necessary guidance on the chapter content and structure including grammar corrections and correcting sentence structure in order to clarify the sentence meaning.

3. The other two co-authors are **Nick Drake and Kevan Mckenzie** from Scottish Water who has supported this PhD project by providing necessary network access, data provision and equipment facilities.

Mr. Iftekhar Zaman Sunny	Dr. Stewart Husband	Mr. Nick Drake
1st author	2nd author	3rd author

Mr. Kevan Mckenzie	Prof. Joby Boxall
4th author	Last author

6.1 Abstract

Trunk mains are high risk critical infrastructure where poor performance can impact on large numbers of customers. Both quantity (e.g. hydraulic capacity) and quality (e.g. discolouration) of trunk main performance are affected by asset deterioration in the form of particle accumulation at the pipe wall. Trunk main cleaning techniques are therefore desirable to remove such material. However little is quantified regarding the efficacy of different maintenance interventions, or longer term changes following such cleaning. This paper presents an assessment for quantity and quality performance of a trunk main system pre, post and for twelve months following cleaning using pigging with ice slurry. Hydraulic calibration showed a 7 times roughness height reduction after ice slurry pigging, evidencing substantially improved hydraulic capacity and reduced headloss. Turbidity response due to carefully imposed shear stress increase remained significant after the cleaning intervention evidencing that relatively loose material had not been fully removed from the pipe wall. Overall the results demonstrate that cleaning by pigging with ice slurry can be beneficial for quantity performance, but care and further assessment may be necessary to realise the full quality benefits.

Keyword: Invasive cleaning, hydraulic roughness, discolouration risk

6.2 Introduction

One of water company's primary responsibilities is to operate and maintain their distribution network performance to ensure the continuous supply of safe, high water quality. As part of the drinking water network, transmission (trunk) mains are categorised as critical infrastructure as poor performance can impact a large numbers of downstream customers. Due to strict operational and quality regulations and concern regarding potential consequences, UK water companies have tended to avoid operational activities associated with trunk mains (Husband and Boxall, 2015). However this is becoming unavoidable and water utilities rehabilitation programs now include large undertaking for the cleaning of large diameter mains (i.e. trunk mains) to manage asset resilience and reduce water quality risks. Considering the massive total expenditure allocated for cleaning interventions, infrastructure performance assessment both for pre-post cleaning water quality and quantity are vital to justify the investment.

Quantity performance e.g. hydraulic capacity and pipe roughness can impacts on the quantity of water received by the consumer, fire flow capacity and energy (pumping) costs. Continuous fouling, tubercles and scaling can increase hydraulic resistance and reduce effective pipe diameter (Boxall et al., 2004). Microbial activity on pipe wall can also raise boundary resistance and affect hydraulic capacity (Cowle et al., 2014).

Discolouration is the water quality issue most apparent to the customer, causing the highest contact rates (i.e. number of contacts per 1000 population per year) worldwide. Particle size analysis demonstrated that discolouration processes are dominated by small particulate material (2-25 μm), thus their behaviour is unlikely to be dominated by gravity driven processes, rather continuously and ubiquitously attaching to the pipe wall by a complex combination of physical, chemical and biological processes (Boxall et al., 2001). The internationally validated PODDS (Prediction of Discolouration in Distribution Systems) model has developed and later verified that these particles are structured in stable cohesive layers and are released in to the bulk water once an excess shear is imposed (Boxall and Saul, 2005). Recent studies have indicated that biofilms are a key component of the discolouration process. facilitating inorganic particle absorption within the organic matrix (Douterelo et al., 2014; Husband et al., 2016). PODDS concepts are well accepted for smaller diameter pipes in the distribution system and are started to be shown valid for large diameter transmission mains (Husband and Boxall, 2015).

As infrastructure ages, particulate material attached to the pipe wall can create a significant discolouration risk and reduce hydraulic capacity (Cook and Boxall, 2011; Shahzad and James, 2002). To remove accumulated material, water utilities often use invasive cleaning strategies as part of their rehabilitation programs (AWWA, 2014). It is well established that invasive cleaning (e.g. ice pigging, air scouring, swabbing) can remove significant amounts of accumulated materials and biofilms from operational trunk mains (Ellison, 2003; Friedman et al., 2012). However, little is quantified regarding the efficacy of such interventions in terms of either quantity or quality improvement and how this changes over time following the intervention.

The aim of this paper is to investigate the quantity and quality performance benefits of an in-service trunk main invasive cleaning program. Quantity performance of the selected trunk main was assessed through hydraulic modelling of monitored pre and post invasive cleaning flow and pressure data, with performance improvement evaluated by change in calibrated roughness height. Quality performance was assessed by monitoring, modelling and comparing the turbidity response due to controlled increase in hydraulic conditions pre and post intervention. Post cleaning evaluations were repeated over a twelve-month period to explore longer term performance changes.

6.3 Methodology

6.3.1 Selected network characteristics

The selected trial trunk main was 2.4 km of 228 mm internal diameter (D) asbestos cement (AC) pipe. In this case, trunk main was defined by operation providing supply from a service reservoir into downstream distribution zones, with no consumers directly connected. The supplied DMAs (District Metered Area) were mostly residential with consistent demand across the year with sub-daily variations. The downstream network had a demand driven diurnal daily flow pattern with an average downstream pressure of 42 m and typical daily demand profile varying between 6 and 20 l/s (0.14-0.48 m/s). The trunk main operates under gravity, with a low point in the long section as shown in Figure 28a.

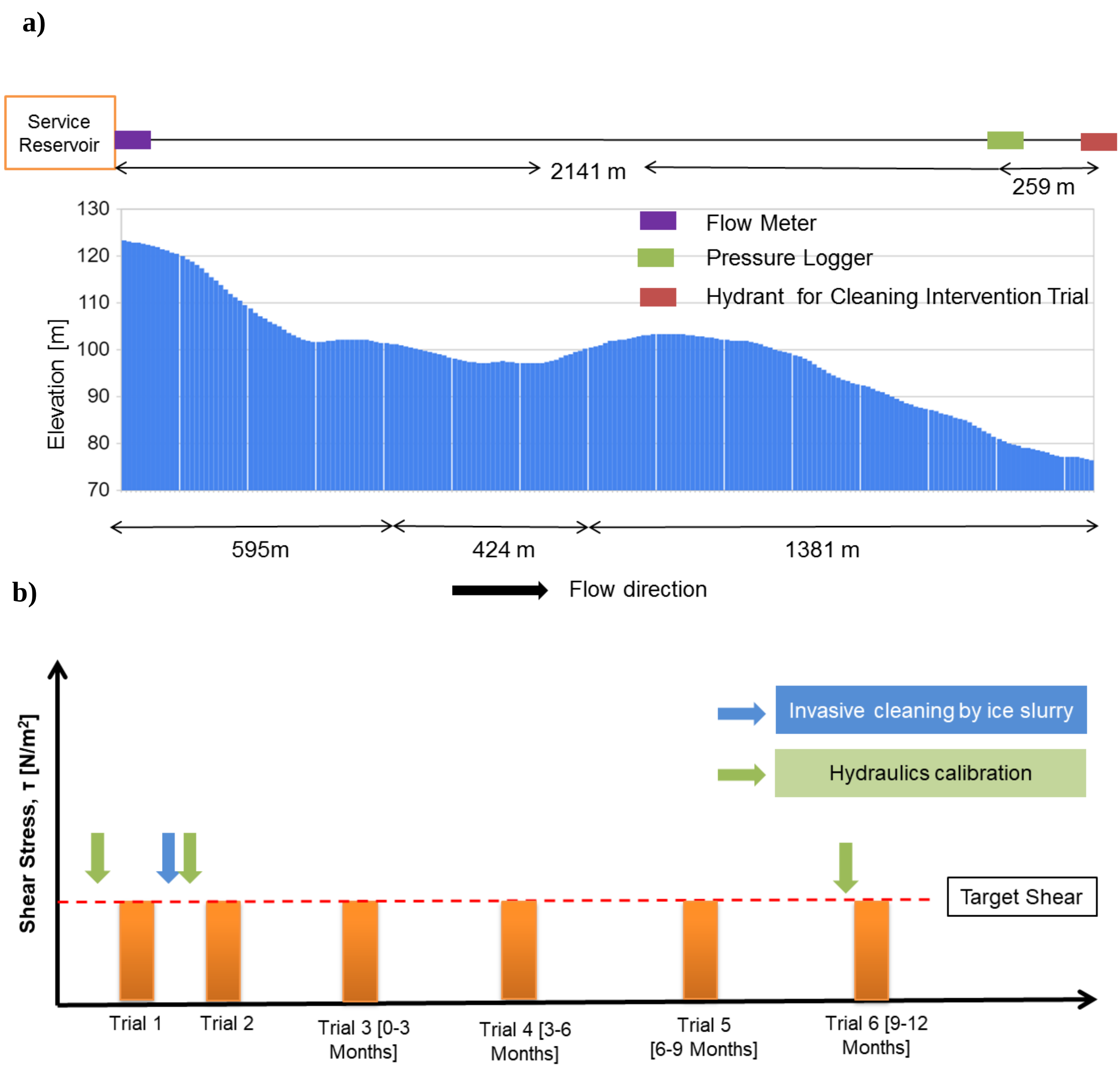

Figure 28: Network schematics with field plan a) Trunk main layout, monitoring points with elevation profile, b) cleaning interventions planning and timelines

6.3.2 Fieldwork procedure and monitoring

The trunk main was built around 40 years ago. No known cleaning intervention have been implemented since it was commissioned. As part of a scheme to reduce discolouration customer contacts in the supplied DMAs and to remove particulate material and biofilm attached to the pipe wall, pigging with ice slurry was selected and implemented (Moore, 2013; Quarini, 2002). The method uses ice slurry to form a dynamic plug which increases shear on the pipe wall to dislodge built-up material. A site-specific amount of semi-solid ice slurry was pumped through a UK standard washout hydrant at the trunk main inlet and emitted from a hydrant 2.4 km downstream. Before cleaning, the main was isolated from supply to ensure no mixing of water into supply with the semi-solid ice pig.

The trunk main served three separate downstream DMAs, with no connections over the 2.4 km length selected for cleaning. This layout ensures constant flow over the entire pipe length. Flow at the inlet, service reservoir level data and downstream pressure data allow for accurate hydraulic calibration, quantity performance. Pre and post pressure data was collected using Syrinix Transientminder loggers with 15-minute resolution. Flow was monitored continuously at the service reservoir outlet using existing instrumentation, again at 15-minute resolution.

Quality performance was assessed by imposing carefully managed flow increases and monitoring for any turbidity response, see Figure 28b. From the PODDS concepts the imposed excess (above normal daily peak) shear stress would induce mobilisation of loose material associated with discolouration, with repeated operations of the same magnitude providing insight into any inter-period accumulation or other change in material layers. Managed increases in system shear stress were imposed through a hydrant standpipe. Flow increases were planned such that turbidity responses were expected to be well within regulatory limits (4 NTU at customers tap in the UK). These trials were executed before, to establish a base condition and just after invasive cleaning to assess the amount of material left on the pipe wall and quarterly thereafter to explore subsequent change. All flow conditioning trials were operated with repeatable conditions i.e. similar time of day, duration, locations, equipment and section of trunk main to ensure the trial results were comparable. To monitor the downstream turbidity response, two ATI NephNet turbidity loggers were used with a 1-second sampling interval. The ATI turbidity loggers were calibrated under laboratory conditions and two loggers used to provide dual validation. Spot checks against HACH handheld turbidity instrument, calibrated against formazin turbidity standards, were also undertaken. A specially designed ABB flow meter attached to a UK standard hydrant standpipe from Langham industrial controls was used to measure flow (and therefore shear stress) with local manual control of a gate valve.

6.4 Results and Discussions

6.4.1 Pipe Cut Out

A pre-intervention pipe cut out was taken from the trunk mains low point (see Figure 28a) to assess the pipe's internal condition and amount of accumulated material present on the asbestos cement pipe wall which is shown in Figure 29. From the visual assessment, accumulated material can clearly be seen around the full pipe circumference, supporting the PODDS model concepts. The cut out was taken at the longitudinal low point, such that all gravitationally driven self-weight settling processes that would have led to invert deposits were explored, with none being found.

Figure 29: Pre-cleaning intervention pipe cut out

6.4.2 Hydraulic capacity assessment

Hydraulic models were developed and simulated in standard EPANET software (Rossman, 2000). The hydraulic model was calibrated using monitored flow as an input and then minimising visual dissimilarities and maximising correlation coefficient (R^2) between downstream simulated and measured pressure. While pipe roughness (k_s) alone can produce an accurate simulation of observed pressure, inaccurate representation of velocities which can be significant for the quality application can persist. This is because hydraulic calibration is an indeterminate problem space where various combinations of diameter and roughness can produce similar headloss and hence downstream pressure. Calibration optimisation processes should also consider changing pipe internal diameter particularly for large roughness heights (Boxall et al., 2004). During the model construction, minor losses were incorporated as EPANET loss coefficient inputs, determined from the EPANET manual

(Rossman, 2000). However, these values were not considered as calibration variables and fixed throughout the simulations so effects would have been constant. The trunk main studied had no known leakage, as assessed through night line analysis. The effect of any unknown background leakage would have been manifest in the flow data that was used as an input to the model. The night line was not observed to change from the start to the end of the monitoring period (other than due to known operational changes) suggesting no new leakage occurred during the study. The estimated boundary condition of pipe roughness and the diameter using Boxall et al. (2004) concept has been applied to the PEST (Doherty, 2005; Méndez et al., 2013) in conjunction with the EPANET model to determine the best possible solutions comparing simulated and measured downstream pressure. The optimised paired value (roughness and diameter) solution was constrained by the original pipe diameter of 228 mm. Figure 30a shows the flow and simulated and measured pressure data for pre-invasive cleaning. As the main is around 40 year old AC, it was expected that it might have relatively high roughness due to continuous material fouling. From the optimisation, the best achievable result for pre-invasive cleaning trial was 6.8 mm pipe roughness and 215.0 mm effective diameter.

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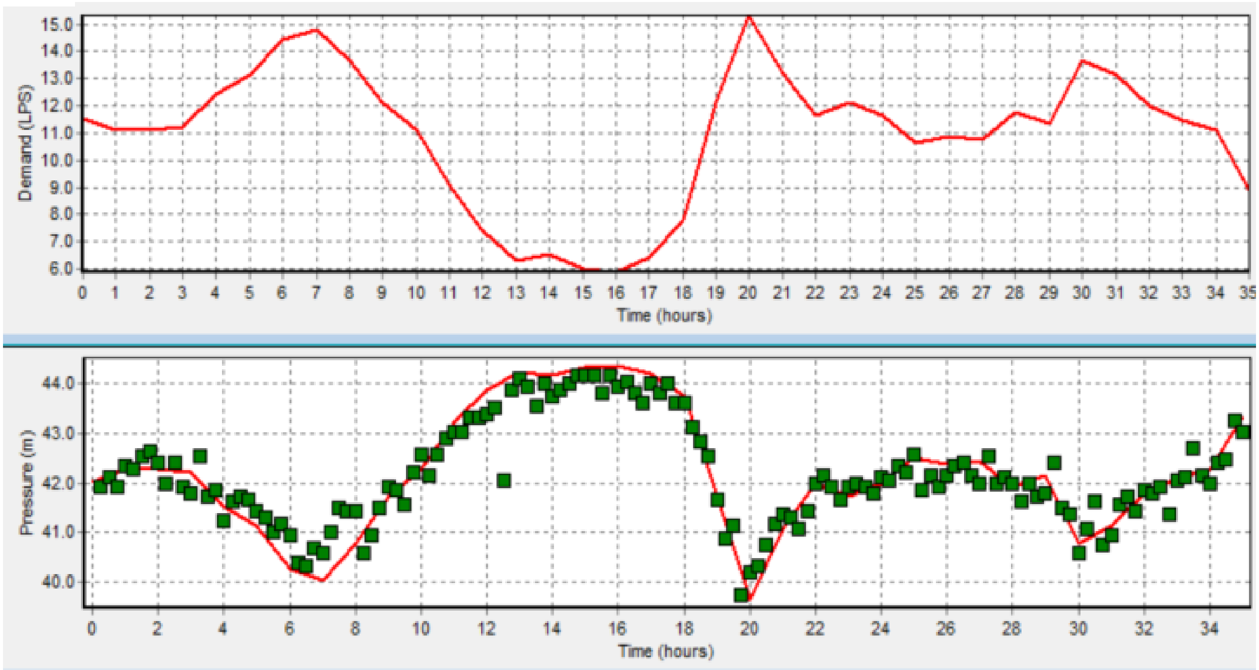
a)



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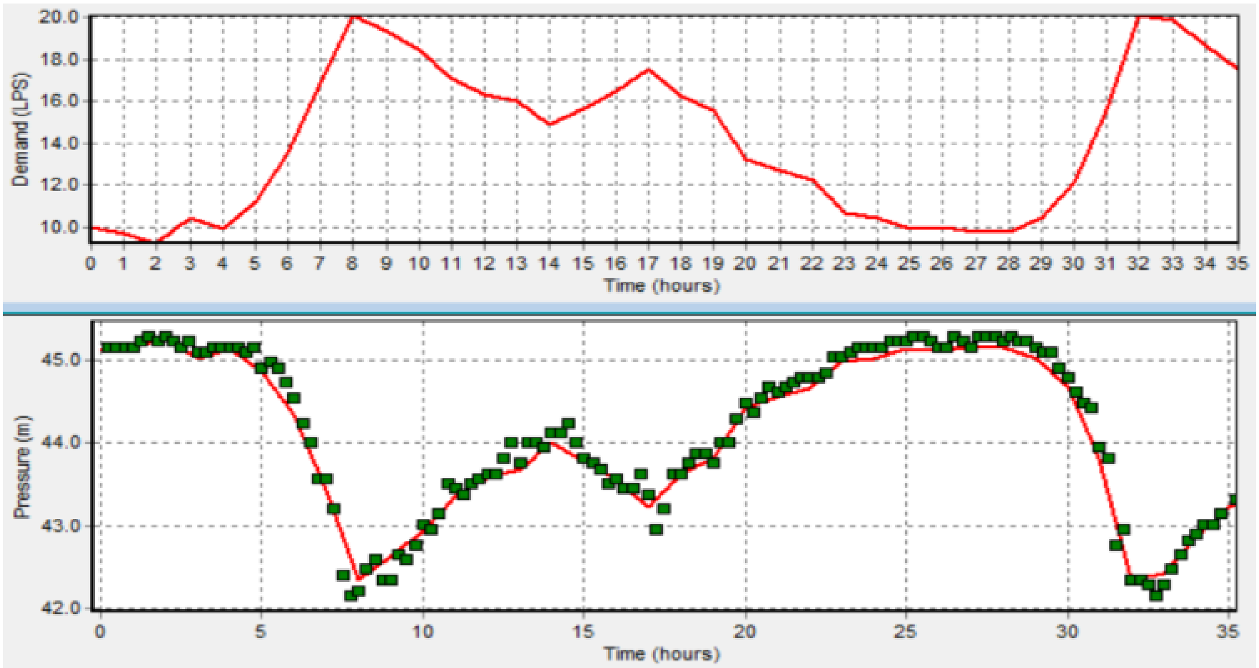


Figure 30: Pre and post invasive cleaning hydraulic simulation in EPANET. Demand in l/s (top plot) and simulated and measured pressure head in m (bottom plot). a) pre cleaning b) post cleaning.

After the ice-slurry cleaning process, a similar monitoring program was conducted. With the new monitored pressure and flow data, the hydraulic model was re-optimised (Figure 30b), with the best model fit achieved with a pipe roughness of 1.0 mm and effective diameter of 227.4 mm. Thus, from hydraulic model optimisation, a seven times reduction in roughness height was found after the invasive cleaning. This demonstrates improved mains carrying capacity and indicates that the ice slurry intervention removed material layers that cause significant hydraulic losses.

A similar pressure and flow monitoring program was conducted 12 months after the invasive cleaning to quantify any further change of hydraulic capacity. Unfortunately, practical constraints were such that the data necessary for detailed hydraulic calibration was not collected for all events. The calibrated roughness was after 12 months found to increase to 2.3 mm and effective diameter reduced to 224 mm. This suggests longer term accumulation, continuous particulate fouling that impact on the hydraulic capacity. A correlation between change of roughness and turbidity response potentially indicates the growth of material on pipe wall over time; however previous work (Boxall et al., 2003) has suggested site specific change in roughness (~0.01mm) corresponding to notable turbidity (~10NTU) response is significantly less than the accuracy of the hydraulic calibration possible here. Table 1 presents all the diameters and roughness values.

Table 7: Hydraulic parameter optimisation results for pre-post and 12 months after invasive cleaning

Hydraulic parameters and calibration efficiency	Initial mean diameter	Pre invasive cleaning (Optimised)	Post invasive cleaning (Optimised)	+12 months post invasive cleaning (Optimised)
k_s [mm]	----	6.82	1.05	2.28
Diameter [mm]	228.04	215.00	227.40	224.04
R^2 [-]	-	0.9424	0.9681	0.9227

6.4.3 Water quality assessment

Water quality performance was assessed by measuring the discolouration response due to imposed excess shear stress, repeated as set out in Figure 28b. Figure 31 presents daily demand and applied shear stress during the first, second and third of these increases in flow (hence change in shear stress) and the ice slurry pigging. Typical maximum daily shear stress before the cleaning intervention was about 1.5 N/m^2, estimated using calibrated roughness values. Due to operational circumstances, daily peak demand had increased after the intervention for more than a month and as a result, daily shear stress was also altered. From 27 August 2015 till 16 October 2015, new properties were connected to the downstream distribution zone fed from this trunk main due to repair work in a neighbouring zone. About 3 l/s demand was increased and transported to the downstream reservoir during this process which can be confirmed from the constant night line profile for over two months. Revised maximum daily shear stress after invasive cleaning intervention calculated from improved k_s value was 1.0 N/m^2 and later it was changed to 0.6 N/m^2. This value persisted throughout the following 12 months of monitoring. A planned night time downstream network flushing was undertaken from 22nd September till 23rd September (2 nights). Also, there was a downstream burst event recorded as starting on 24th September and continuing until 25th September (Figure 31). Unfortunately, there was any turbidity loggers deployed on this trunk main which could have captured the continuous mobilisation response due to the burst event. These events could have mobilised accumulated material as it was higher than trial 2 event and potentially influence trial 3 responses.

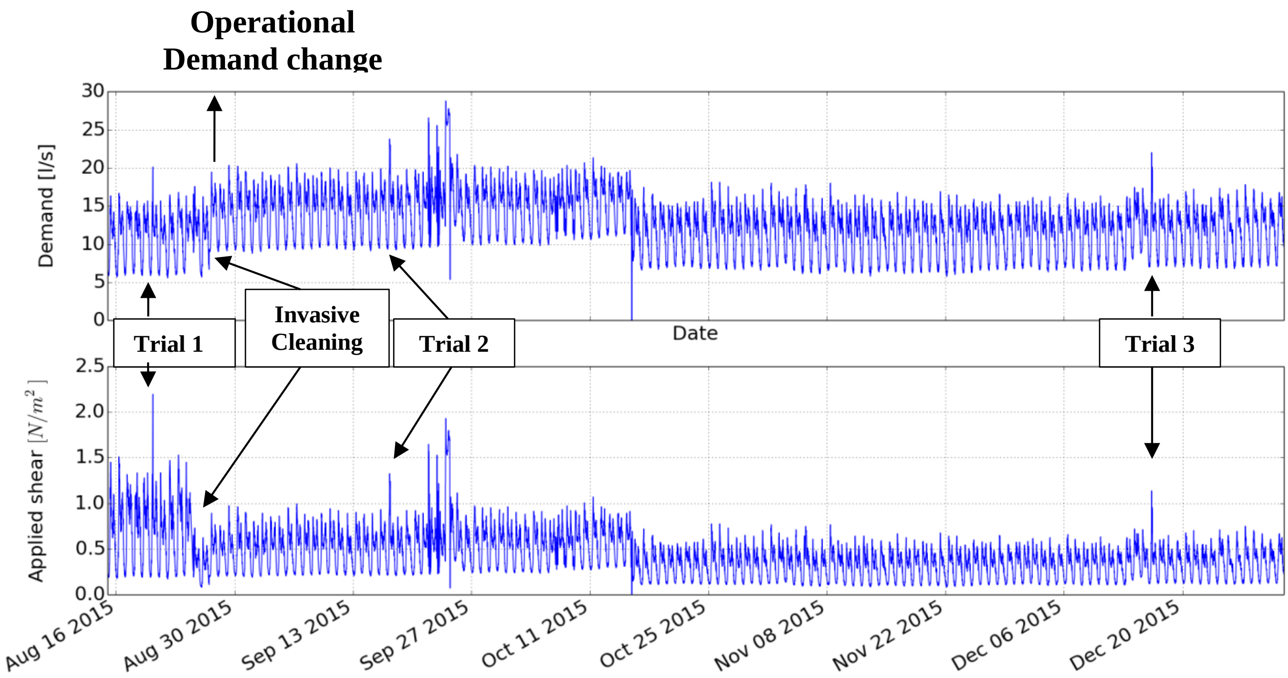


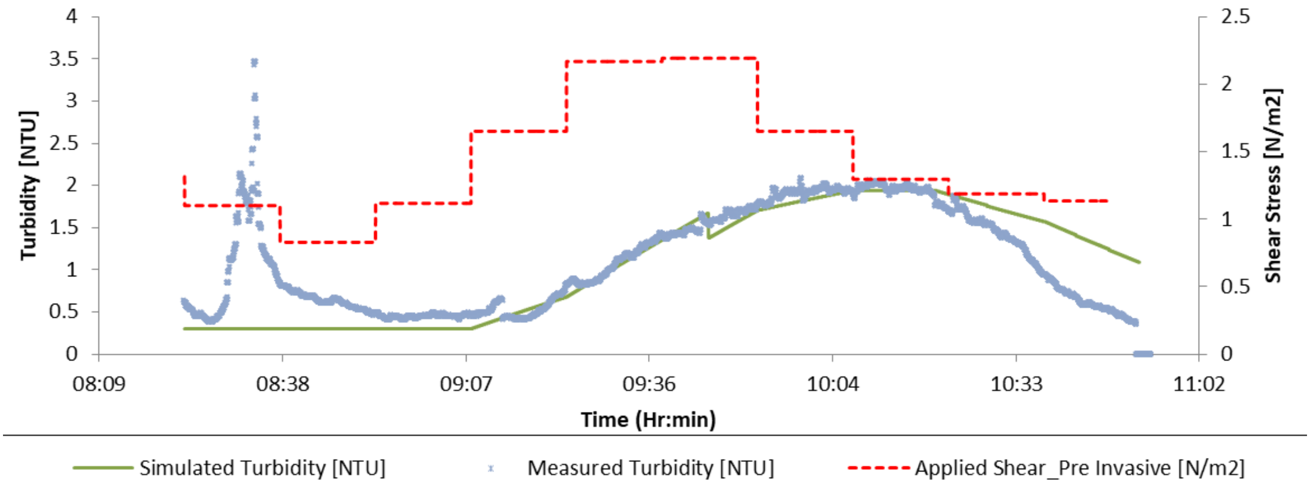
Figure 31: Daily demand in l/s and applied shear stress in N/m2 variations from August, 2016 till December, 2016

Figure 32a shows the measured and simulated turbidity response due to shear stress increases before the ice slurry pigging intervention. It is evident from Figure 32a that material started to mobilise during the shear step of 1.1 to 1.65 N/m^2, consistent with a normal daily max shear stress of 1.5 N/m^2. Maximum shear stress during the trial was 2.20 N/m^2 generating a measured peak turbidity of about 2.0 NTU. To avoid regulatory turbidity limit (4.0 NTU), shear stress was reduced stepwise to 1.13 N/m^2 and it continued until the turbidity response had returned to pre-trial levels. An initial turbidity spike was observed around 8:30 am due to connection and opening of the hydrant.

To assess the discolouration risk from the main after it had been invasively cleaned, a similar trial was conducted 3 weeks after the pigging intervention (see trial timeline in Figure 28b). Figure 32b shows that despite the cleaning, material was mobilised from the pipe wall by only a small increase in excess shear stress. The maximum operated shear stress during the second trial was 1.32 N/m^2 and peak turbidity was about 1.0 NTU. As with other case studies, the ice slurry pigging was shown to remove significant amounts of materials. However, these results show that loose material was present in the pipeline only 3 weeks after the invasive cleaning.

Previous research has suggested that ice plug pressure or friction forces can drop as the trial continues (Candy et al., 2010; Shire, 2006). Therefore, potentially the cleaning performance was inadequate to remove all the materials during ice plug formation and movement along the pipe length. As noted previously the trial main had a low point in its longitudinal profile, as shown in Figure 28a. Contractors for the invasive cleaning program suggested the ice plug may have dropped pressure while flowing upwards from the dip section, possibly leaving material there. However, Figure 32b shows a linear increase in turbidity hence mobilisation of material from over the full pipe length with no spike in turbidity associated with the travel time from the trunk main low point

a)



b)

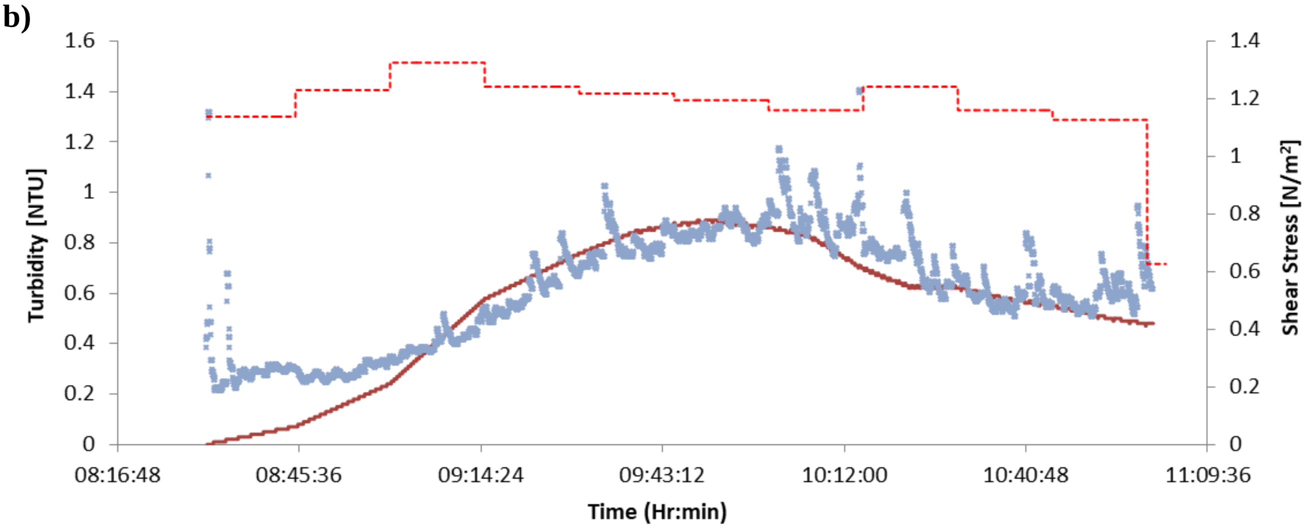


Figure 32: Measured and simulated turbidity response a) before the invasive cleaning trial b) after the invasive cleaning trial

Results of metal samples during the trials are shown in Figure 33, expect trial 2 as samples could not be collected during the trial durations. Figure 33a shows that the concentration of manganese (Mn) was high and occasionally exceeding the UK regulatory prescribed concentration value (PCV) value of 50 μg/l. Iron and aluminium concentrations are also shown to be significant, although well below the UK PCV limit. Figure 33b presents the results for calculated metal concentrations for an equivalent 1.0 NTU limit. Manganese PCV is likely to be exceeded during all trials at this threshold suggesting high manganese content in the bulk water. From this it could be suggested that the accumulation or fouling effects are driven by manganese and other metal (e.g. iron and aluminium) precipitation from the bulk water which is consistent with previous research findings (Boxall et al., 2003; Husband and Boxall, 2011; Seth et al., 2004). However, a complete conclusion about the inorganic particles responsible for the observed discolouration cannot be drawn from this sampling study alone as undisturbed sampling data from the trunk main were unavailable. Also the previous work has indicated that biological processes impact on material accumulation and hence influence discolouration risks (Gauthier et al., 1999; Husband et al., 2016).

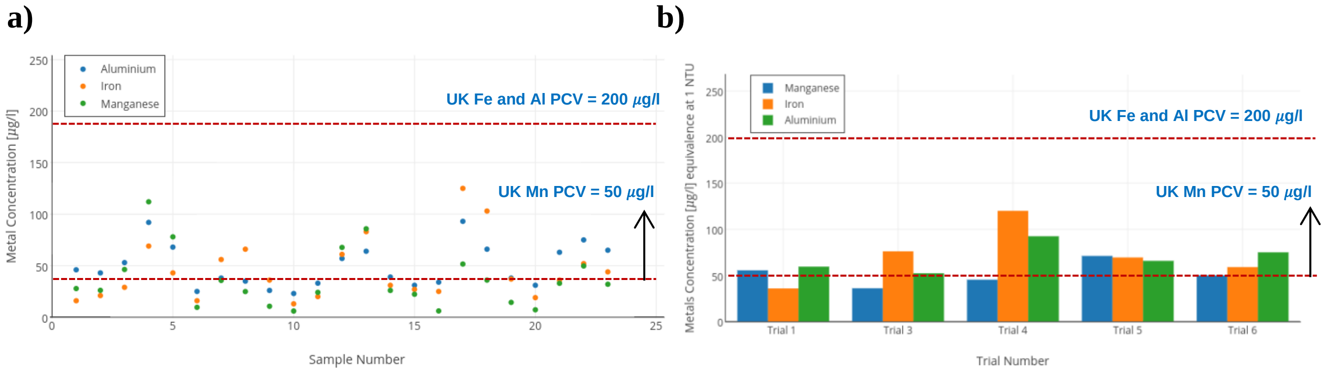


Figure 33: a) All metal sampling during trial durations, b) metal concentration equivalence at 1.0 NTU

As can be seen from Figure 32, PODDS model simulated successfully both pre and post shear stress trial induced turbidity responses. However, the invasive cleaning changed the accumulated layer conditions from pre to post in such a way that, it is not possible to compare the modelling results without a continuous mobilisation-accumulation tracking facility which PODDS model cannot facilitate. It is possible to simulate the discolouration response for a set of flow (or shear) increases from trial 3 to 6 taking information from Figure 32b model parameters, however due to the limited continuous flow and turbidity data, comparisons made here are only with fieldwork results. Flow increases and subsequent material mobilisation were repeated at three monthly intervals to assess the ongoing accumulation of loose material. Due to operational constraints, the imposed shear stresses were not exactly the same, as in Figure 31. Hence results are not directly comparable. In order to aid comparison, the time series data was converted to ‘volumetric turbidity’ due to imposed shear increase to estimate the material release rate per unit wall area. This was calculated by integration of the time turbidity plots with respect to the amount (flow rate with time) of water used and divided by the maximum imposed shear stress and pipe internal wall area. This effectively accounts for differences in mass flux but assumes mobilisation is linear with flow rate. While the last assumption is not valid, it is an acceptable simplification over the range of different excess shear stress imposed here. Table 2 presents the test parameters used to calculate material release rate for all trials. Though the roughness and diameter values were unknown in trial 3, 4 and 5, paired parameter values were assumed to be equal to trial 2. To calculate imposed excess shear stress addition to the table 2, discolouration material density (ρ) and gravity was used at 1100 kg/m^3 (Boxall et al., 2001; Ryan et al., 2008) and 9.81 m/s^2.

Table 8: Test parameters for material release rate calculations

Parameters	Unit	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
Internal diameter [ID]	m	0.215	0.2274	0.2274	0.2274	0.2274	0.22404
Pipe roughness [k_s]	mm	6.82	1.05	1.05	1.05	1.05	2.28

Figure 34 summarises these amounts of volumetric turbidity mobilised from all trials, together with indicative service reservoir outlet seasonal water temperature collected by spot samples as part of the regular sampling program. As expected the pre-invasive cleaning trial generated relatively higher turbidity response compared to post cleaning trials. However, the 3 weeks post invasive cleaning amount was high as well suggesting that the material was able to regenerate quicker after invasive cleaning compared to the conditioning trials, rapidly developing to re-establish equilibrium between cohesive layer forces and daily peak shear stress, or that material loosened by the slurry was not fully removed. While the invasive cleaning was effective in removing a significant amount of historical accumulations, the remaining loose particles was not necessarily mobilised easily through ice slurry and hence represent discolouration risks. After 12 months this weaker material risk had returned, but the stronger material apparently responsible for the initial roughness height had not. The following 3 month period, where temperature was lowest shows the least amount of material accumulated and subsequently mobilised by the controlled flow increase, while the final 3 months period where temperature was greatest showed the overall highest levels of mobilisation of weakly adhered material. Hence this indicates a temperature influence on material regeneration process in this trunk main. Previous research evidence has also suggested a temperature impact on material regeneration and discolouration processes and this potentially associated with microbial activity (Blokker and Schaap, 2015; Sharpe, 2012). However, as a single trunk main study it is not possible to confirm temperature and pipe material influcne on biofilms and hence significance on discolouration risks without investigating similar test profiles on varying pipe materials.

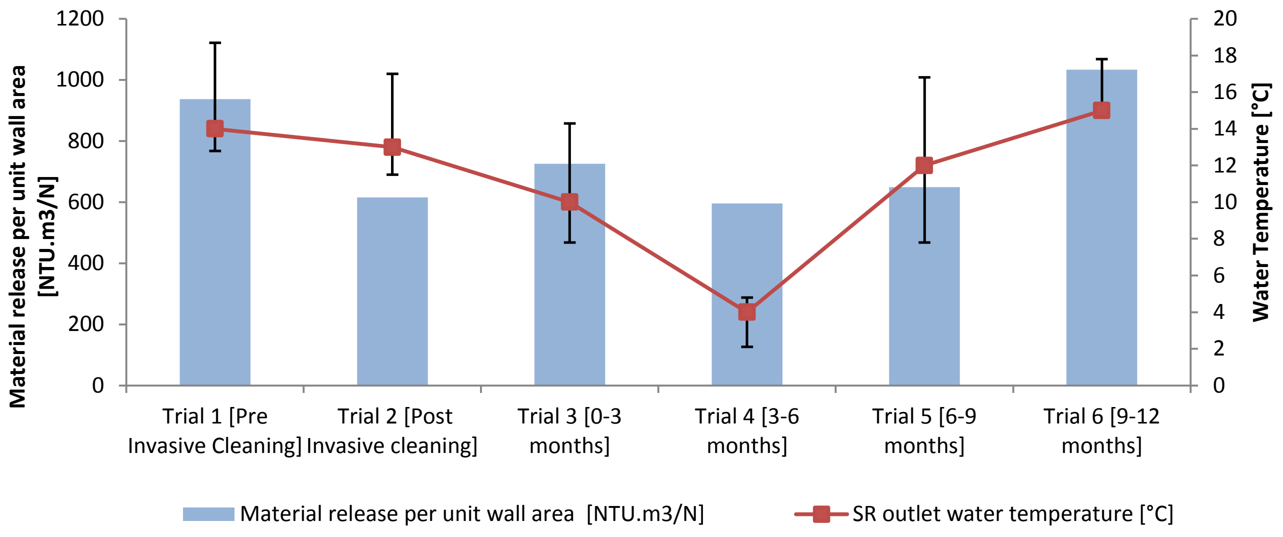


Figure 34: Volumetric turbidity output during flow conditioning trials with service reservoir outlet temperature with seasonal variations

6.5 Conclusions

The study investigates pre, post and long term, quality and quantity performance of a trunk main subject to invasive cleaning by ice slurry pigging. Benefits expected due to invasive cleaning included an improvement in hydraulic capacity and a reduction in discolouration risk. The findings from the fieldwork are summarised below:

- Hydraulic modelling and calibration showed pipe roughness reduced by about 7 times after semi-solid ice slurry cleaning intervention. However, monitoring and modelling after 12 months showed that the roughness had slowly increased after the intervention suggesting continuous material fouling impacting on the hydraulic capacity.
- Pipe wall material mobilisation through controlled shear stress increases removed significant material after the selected invasive cleaning process. This indicates that loose particles remained on the pipe wall and that there was still a risk of discolouration after this invasive cleaning intervention was performed.
- Repeated flow conditioning trials showed ongoing material accumulation, evidence of ongoing endemic processes.

7. Simulating Long Term Discolouration Behaviour in Large Diameter Trunk Main

Declaration

The chapter seven is in a format that can be further developed and then be suitable for submission as a journal paper. The contribution of the main author and co-authors are following:

1. **Iftekhar Zaman Sunny** is the PhD candidate and 1st author and major contributor to this published chapter. As a part of his PhD research, he has formulated the aims, developed the methodology, monitored and analysed necessary data and outlined conclusions for this publishable paper. Primarily he has designed and written the chapter having inputs from the co-authors as stated in point 2.

2. **Prof. Joby Boxall and Dr. Stewart Husband** are the primary academic co-authors of these chapters. They have supervised the PhD research project and provided critical input into the research methodology. They have helped to define and refine the aims, overall structure of the thesis, interpretation of results and formulation of discussion points. They also have provided necessary guidance on the chapter content and structure including grammar corrections and correcting sentence structure in order to clarify the sentence meaning.

Mr. Iftekhar Zaman Sunny 1st author	Dr. Stewart Husband 2nd author	Prof. Joby Boxall Last author

7.1 Abstract

Prediction of long-term turbidity behaviour is essential for managing trunk main discolouration risk as quality failure can cause significant impacts on customer perception and potential financial penalties in the UK. The work reported here provides the first long-term continuous turbidity time series and modelling of discolouration behaviour in large diameter mains, simulating both the material accumulation and mobilisation processes successfully. The Variable Condition Discolouration (VCD) model that tracks varying strength material conditions on pipe walls is validated on multiple trunk main systems with over a years data including notable turbidity responses from both managed and unplanned hydraulic events. The model is shown capable of simulating the measured response with an average peak turbidity accuracy of ±0.25 NTU within a single extended period simulation. The ability to simulate varying magnitude and temporal hydraulic induced turbidity events effectively validates the modelling approach for encapsulating accumulation processes that occur at all shear strengths simultaneously. The similar accumulation rates for studied trunk mains suggest that these are transferable and discolouration risk remain similar over time irrespective of cleaning intervention. The understanding of material accumulation processes and the ability to simulate long-term turbidity behaviour can be used to inform discolouration risk management proactively and optimise network maintenance frequencies so that complex and expensive trunk main cleaning strategies can be avoided.

Keywords: Shear stress, accumulation process, turbidity simulation

7.2 Introduction

Water supply from treatment to customer tap is designed to ensure that it is safe for human consumption and compliant with stringent regulatory limits. Even after modern treatment facilities, particles along with solute remain in the bulk water and are transported downstream and can accumulate on pipe walls. This accumulated material can promote discolouration incidents due to hydraulic disequilibrium. Discolouration is the most apparent water quality failure reported around the world with customer contacts often used as a key performance indicator by the water authorities and their regulators (Polychronopolous et al., 2003, DWI,2016). Discoloured water sample can also breach other quality parameters as well, e.g. iron (Cook, 2007). However, these events are sporadic in nature, and relatively short duration as mostly induced from random hydraulic disturbances, e.g.

burst. As a result, they are unlikely to be captured by regulatory sampling. Discolouration incidents due to hydraulic events are particularly significant in large diameter transmission (trunk) mains as they can provide risk to large downstream populations. In the UK discolouration contact targets have been set as an indicator of delivered water quality with significant financial penalties or reward depending on annual performance. Although customer observed events are typically recorded as occurring in downstream District Metered Areas (DMA), 30-50% of discolouration events have been identified as originating from the upstream trunk main highlighting criticality of trunk main discolouration maintenance (Cook et al., 2015). To simulate and predict turbidity behaviour for large diameter trunk main, it is essential to understand how discolouration material behaves under varying hydraulic conditions. While discolouration risk is primarily induced from rapid mobilisation of accumulated materials, little is known about how these material returns on the pipe wall with no known model yet able to simulate this process effectively. While short-term discolouration responses are important to predict, long-term accumulation rate needs to be considered. Therefore a comprehensive discolouration model is required which can track discolouration material condition on pipe walls and simulates changing discolouration risk by encapsulating both mobilisation and accumulation would benefit operators predicting short-term turbidity response over a long periods.

7.3 Background

7.3.1 Discolouration processes: Mobilisation mechanism

Discolouration was traditionally conceptualised as the re-suspension of gravity-driven sediments. Extensive study of discolouration particle size distribution and density analysis revealed that the particles responsible are small in size and between 2-50 μm (Boxall et al., 2001; Ryan et al., 2008; Vreeburg, 2007). Hence self-weight effects are small and when re-suspended, they only settle due to the gravitational effects during prolonged quiescent conditions (Boxall et al., 2001). Similar phenomenon is suggested by UKWIR, (2001) that below 60 μm particles are prone to remain suspended unless quiescent conditions occurs. Particle accumulation alone by traditional gravity settling processes is also not considered valid in water distribution systems as flow is mostly in turbulent conditions (Blokker et al., 2010) and no sedimentation effect was found for a typical stagnation period in a dead-end pilot-scale areas (Smith et al., 1999).

Discolouration events are typically observed following hydraulic disequilibrium (Blokker and Schaap, 2015a). This change of network hydraulic conditions, e.g. burst or demand rezoning, may increase velocity and therefore shear stress (τ_C) higher than the pipe network recently experienced. This will cause detachment of particles into the bulk flow and hence create discolouration as this propagates downstream (Boxall et al., 2003b; Husband and Boxall, 2010). Flushing fieldwork has demonstrated that each step increase of shear stress releases additional material suggesting the accumulated material exhibits cohesive strength properties and are structured in varying strength with weaker layers mobilising earlier than stronger ones (Boxall et al., 2001, 2003b; Husband and Boxall, 2010). On the contrary, if material is comprised of loose deposits as conceptualised by sedimentation, all material will release instantaneously. A number of investigations have demonstrated particle mobilisation in response to velocity and shear stress and concluded that particles cannot bind in non-cohesive conditions unless the peak velocity is sufficiently low (Pothof and Blokker, 2012; Vreeburg, 2007). This suggests that accumulating materials likely has cohesive properties, a result consistent with findings from the University of Sheffield fully temperature controlled experimental pipe facility (Husband et al., 2008).

7.3.2 Discolouration process: Accumulation mechanism

In several repeated flushing trials, it has been seen that following flushing discolouration material returns, accumulating again on the pipe wall (Blokker and Schaap, 2015a; Cook and Boxall, 2011; Husband and Boxall, 2011; Husband et al., 2010). Repeated flushing also showed amounts of accumulated material during flushing was similar irrespective of seasonal influences suggesting material accumulated linearly over time (Boxall et al., 2003a; Cook and Boxall, 2011).

A number of studies have been aimed to develop an understanding of the material accumulation processes and how it is influenced by other physical, chemical and microbiological processes. Van Thienen et al., (2011) proposed two different accumulation mechanisms, turbophoresis and turbulent diffusion. Both these concepts only describe material transport from bulk water to wall and not how material bind on the pipe wall. These methods are not also applicable for large diameter pipes where turbophoresis is found influential to relatively large particles (>50 μm) and turbulent diffusion applicable only for very low velocities (<4 cm/s). Several researchers have provided evidence that discolouration material accumulates at varying strength cohesive layers at the same time (Husband and Boxall, 2011; Sharpe, 2012). Flushing field work by Husband and Boxall, (2011) in different parts of the UK demonstrated that material released in repeated flushing trials was lower than an initial flushing, indicating that accumulated material had not been completely regenerated after 12 months intervals. Their study, using multiple shear stress step increases, also showed material being mobilised at each step similar to the initial flushing trial. This repeated turbidity response supporting that material accumulation occurring simultaneously across the range of shear strengths. Accumulation processes observed in field studies have also been supported by laboratory trials in a full-scale temperature controlled pipe facility by Sharpe (2012). This study showed material mobilisation occurring across the range of imposed shear stresses with a consistent turbidity response, indicating particle binding on the pipe wall occurring simultaneously for all shear strengths. From all the studies reported, it is evident a continual mobilisation-accumulation cycle is exists that has a relatively consistent behaviour across the full range of shear strength bound material and applied hydraulic forces. This leads to complex material conditions on pipe walls and varying amounts of material could present on pipe wall with different cohesive shear strengths at any given time. Although knowledge of mobilisation and accumulation processes has been gathered from experimental investigations, no known modelling framework encapsulates these simultaneous effects which can then facilitate simulating the long-term turbidity behaviour.

7.3.3 Accumulation process influencing variables

A number of researchers have investigated how quickly material returns of pipe wall or accumulation rates and how different variables influences these rates. Blokker and Schaap, (2015a) showed that with the change in bulk water quality, accumulation rates can be varied. Husband and Boxall, (2011) demonstrated that material accumulation rates on the pipe wall was greatly influenced by bulk water quality. Vreeburg et al., (2008) demonstrated that water treated with ultra-filtration (0.1 μm) reduces material accumulation significantly but still occurs at low rate. Cook and Boxall, (2011) reported that similar percentages of metal concentrations were present in varying cohesive strength samples, indicating layer inorganic composition is uniform irrespective of hydraulic properties and predominantly dependent on bulk water quality. In addition to bulk water quality, material accumulation and hence discolouration risk are influenced by shear stress and velocity (Blokker et al., 2010; Cook and Boxall, 2011; Pothof and Blokker, 2012) and pipe material (Husband and Boxall, 2011). While some studies has showed temperature and microbial influence on discolouration risk (Blokker and Schaap, 2015b; Ginige et al., 2011; Husband et al., 2016; Sharpe, 2012), the variation of accumulation rates seasonally is not proven yet. No correlation was found between pressure and discolouration risk (Gaffney and Boult, 2012), although hydraulic transients could contribute to material mobilisation (Aisopou et al., 2010).

7.3.4 Modelling discolouration risk

Various discolouration models exist which can describe material mobilisation behaviour and hence facilitate discolouration simulation. These include the particle sedimentation model (Ryan et al., 2008) that uses gravity deposit processes contrary to operational evidence (Boxall et al., 2001; UKWIR, 2001) and artificial neural network model (Meyers et al., 2017) which is a data driven model that does not describe the discolouration process or currently transferable across sites. Other discolouration models that use velocity and shear stress as a mobilisation criteria, e.g. discolouration risk model (Dewis and Randall-Smith, 2005) and discolouration propensity model (McClymont et al., 2013), are not validated. The PODDS (Prediction of Discolouration in Distribution Systems) model (Boxall and Saul, 2005) uses excess shear stress criteria for mobilisation, evidenced from the flushing work (Boxall et al., 2001). This cohesive transport model has been validated both for small diameter (Boxall and Saul, 2005; Husband and Boxall, 2010) and large diameter pipe systems (Husband and Boxall, 2015, 2016). Unlike other discolouration models, PODDS has an integrated material accumulation function that is the reverse of simulated mobilisation process where strongest to weakest shear strength material accumulates following mobilisation. However, the accumulation process coded in the PODDS model does not describe the observed accumulation processes from the laboratory (Sharpe, 2012) and field data (Husband and Boxall, 2011) that has been collected and analysed since its conception.

7.3.5 The Variable Condition Discolouration (VCD) model

In 2014, Furnass et al., (2014) proposed the Variable Condition Discolouration (VCD) model to simulate the discolouration behaviour as observed from laboratory and field data. The model captures some key mechanisms which govern discolouration as:

- The model assumes that wall bound cohesive layers remain in equilibrium conditions with recent prevailing hydraulics (τ_c).
- Material at the pipe wall accumulates over full range of shear strength when applied shear stress (τ_a) $<\tau_c$

- Material is mobilised from the pipe wall and entrained and completely mixed with the bulk water due to the imposed excess shear stress (τ_a-τ_c) when τ_a>τ_c. In this context, the VCD model retains the same mobilisation mechanism as the PODDS model (Boxall and Saul, 2005).
- Model is designed to track material across the range of shear strengths with mobilisation and accumulation processes occurring simultaneously.
- The model assumes material adheres uniformly throughout the pipe wall adopting field evidenced flushing data (Boxall and Saul, 2005).
- Model assume weak layer is always on top of stronger layers

The model tracks relative material quantity φ (τ,t), a unitless parameter, bound between [0,1.0] where 0 means no material and 1.0 is a maximum accumulation of material (Furnass et al., 2014). The VCD model simulates discolouration using three empirical parameters, a mobilisation rate = β_e [$N^{-1}m^{-2}s^{-1}$], an accumulation rate = β_r [s^{-1}] and material release coefficient = α [NTU.m.s^{-1}]). The mobilisation rate (β_e) and material release coefficient (α) describe the material mobilisation phenomenon and represent the rate of material release from a pipe wall where β_e is a function of excess shear stress (τ_a-τ_c), and α is linear scaling parameter. The accumulation rate (β_r) describes the rate at which material accumulates on the pipe wall and is a pipe specific property. To reduce modelling complexity, all three model parameters (β_r, β_e, α) are currently designed as a scaler and invariant with time and shear strength.

Furnass et al., (2014) verified the VCD model through synthetic data and then successfully calibrated it for small diameter pipes and a single trunk main from field data. The calibration results demonstrated that the VCD model retains the mobilisation function of the PODDS model, with similar quality of fitting obtained. Suitable data was not available to validate the accumulation functionality for the small diameter pipes, and the trunk main dataset was limited by the quality of the long-term time series data. Thus the accumulation mechanism of VCD model is verified (Furnass, 2015; Furnass et al., 2014), but has not been validated with long term data. The validation of accumulation process (occurs at all cohesive strengths simultaneously) and hence validation of VCD model would allow tracking discolouration response for different hydraulic scenarios and how risk changes over time and can be minimised.

7.4 Aims

The aim of the paper reported here is to assess if the continual mobilisation and accumulation model can simulate the long-term turbidity behaviour of operational trunk main systems and hence provide a useful tool for informing discolouration risk assessment and management. The aim is to test the robustness of the model by exploring its ability for multiple independent trunk main systems supplied from a single water source with varying normal hydraulic and intervention conditions.

7.5 Methods and materials

7.5.1 Experimental design

In order to validate the VCD model's ability to simulate long-term material mobilisation and accumulation behaviour, it is essential to have hydraulic and turbidity time series data that includes notable turbidity responses due to hydraulic changes as well as stable inter duration between events. While such hydraulic events may occur naturally creating a discolouration response, there is no certainty or control. Hence an experimental design was developed involving periodically imposing excess shear stress events, termed flow conditioning, to generate controlled turbidity responses. A key assumption of the VCD model is that cohesive layers accumulate at varying strengths simultaneously. If valid this attribute would enable the model to simulate discolouration behaviour across a range of events, site conditions and to inform change in risk over time. In order to validate this concept, it is therefore essential to implement different magnitude hydraulic events and measure the associated turbidity response to investigate the impact on mobilisation and accumulation. To facilitate this, two different types of flow conditioning events were implemented in two similar trunk mains, one with higher imposed excess shear stress and termed normal flow conditioning, and another with relatively lower excess shear stress events termed passive flow conditioning. For each type of operation a quarterly return interval was established to define material accumulation periods. A third trunk main with flow conditioning only at the start and end of the investigation period was used, to act as a control. Figure 35 shows the different flow conditioning interventions implemented on the three trunk mains to provide the necessary range of events across different strength profiles, periods of accumulation and control. Initial and final target shear increments were similar for all three strategies. The initial shear increment was planned to ensure layer conditions were in similar conditions for all three trunk main at the trial outset. The similar target shear stress at the end of investigation was implemented to allow investigation of the long-term effects on higher shear strength material following the different interventions. While natural hydraulic events may also occur, these planned events with managed conditions ensured that necessary data would be obtained for model validation.

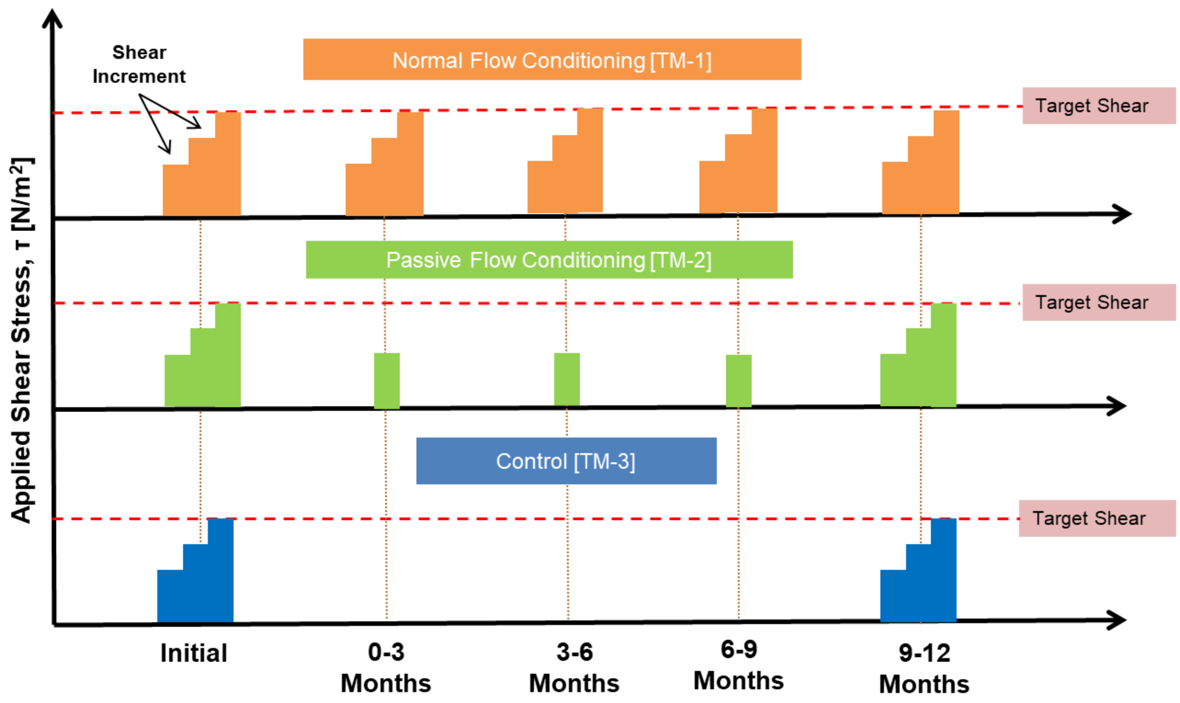


Figure 35: Methodology, procedure and flow conditioning intervention strategy definition and timeline for the three investigated trunk mains

Commencing with a VCD model, empirical parameter calibration requires long-term hydraulic and turbidity data. System flow and pressure data are required for accurate hydraulic representation and travel time, with flow also used to determine shear stress. While collecting this data for calibration purposes may appear only effective during planned flow conditioning events, natural hydraulic events (e.g. bursts) may occur at any time. In addition, planned and unplanned intervening periods facilitate different material accumulation periods, and hence full duration high temporal logging is required to represent system behaviour at any time. Flow, pressure and turbidity monitoring equipment was therefore deployed for continuous capture facilitating single run period simulations to assess the model’s ability to track long-term discolouration behaviour.

As bulk water quality, hydraulic conditions and pipe material can all influence material accumulation rates, for scientific rigour, it is therefore important to minimise these differences across test sites. In defining trials, the three trunk mains to be selected required similar pipe material, supplied from a single water source and with similar hydraulic conditions including shear stress as wall exert force and Reynold numbers for material movement at laminar boundary layers. No known effect of pressure on discolouration has been identified and hence similar pressure regime in the selected trunk mains was not considered during site selection.

7.5.2 Site details and treated water quality

To meet the site selection criteria, three independent trunk mains were selected all supplied from a single water treatment works (WTW) in a UK operational network. The network alignment ensured that the same treated water passed through each trunk main and all were of similar pipe material and hydraulically had similar daily flow, velocity, shear stress and Reynold numbers. For trial purposes, all three trunk mains had similar physical, chemical and biological properties to facilitate comparison of results whilst investigating different imposed hydraulic events. Figure 36 presents a schematic of the investigated network with the main monitoring points indicated. All three trunk mains run independently. TM-2 and TM-3 run parallel to each other over much of their investigated length, although serving separate downstream distribution zones. Selection of the inlet and outlet monitoring points is important to ensure trunk main test sections act as a single pipe length to accommodate the experimental design procedure. The inlet point ensures the incoming turbidity from treated water and and outlet confirming no intermediate connection points, such as to any downstream distribution zone, to ensure hydraulic conditions remains the same. With the trunk mains directly supplying downstream distribution zones, proposed hydraulic events were planned to be conducted from fire hydrants. Continuous and trial measurement logging was also conducted from these locations. Both TM-2 and TM-3 had limited fire hydrant access points with the only available data monitoring location shown in Figure 36.

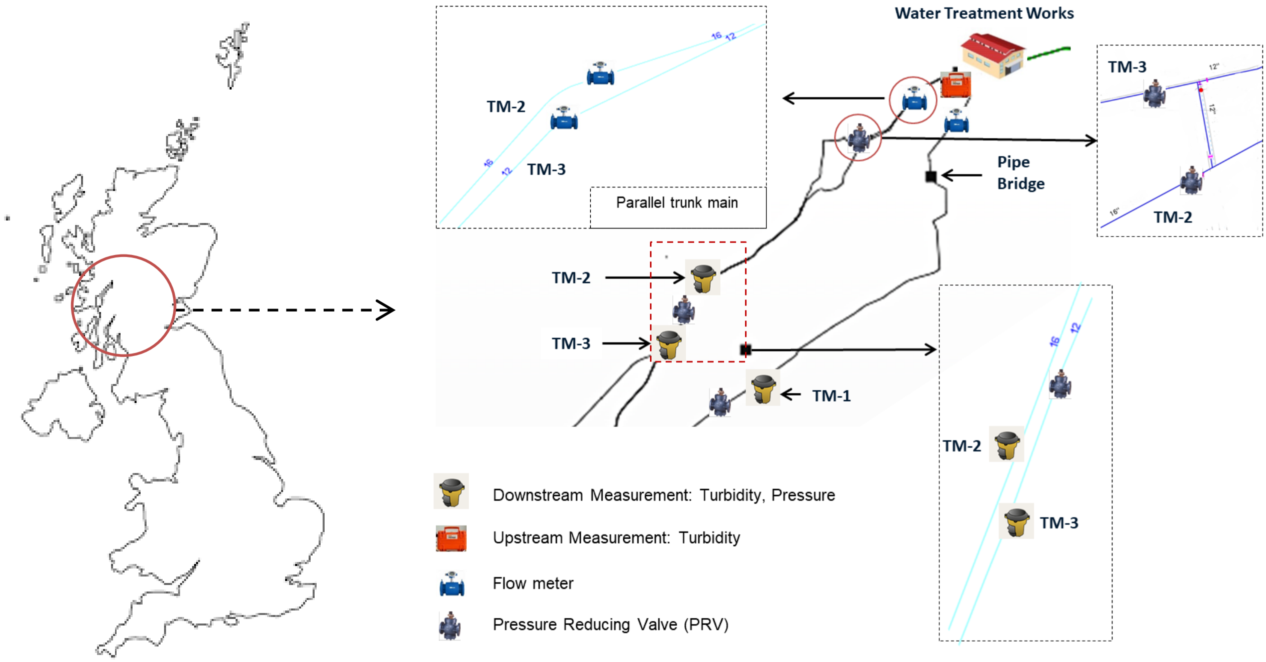


Figure 36: UK site location and schematics of the investigated network showing the water treatment works, the three test trunk mains and instrument deployment locations for continuous measurement. TM-2 and TM-3 are laid parallel, with all cross-connections closed other than during operational events

All test trunk mains were gravity fed from the WTW and laid in mostly semi-urban non-paved areas with moderate vegetation. From Figure 36 it can be observed that by the locations of pressure reducing valves (PRV's), TM-1 was pressurised for full monitoring length without any pressure constraint, TM-2 had partial pressure constraint, and TM-3 pressure reduced over the entire monitoring length. Table 9 summarises the details of all three trunk main hydraulic and PRV properties.

Table 9: Selected trunk mains hydraulic and PRV properties

Trunk main system	Internal pipe diameter, ID [mm] from company record	Pipe material	Length from the WTW outlet to downstream logger [km]	Pressure Reducing Valve (PRV) properties (TM-3 had two PRV separated with comma)	
				Inlet pressure [m]	Outlet pressure [m]
TM- 1	304.8	Partially lined CI	6.4	97.0	19.0
TM-2	406.4	Unlined CI	5.6	44.0	20.0
TM- 3	304.8	Unlined CI	5.9	38.0(a), 79.0(b)	19.0(a), 16.0 (b)
*TM-3 had two PRVs which marked as a = nearer to the WTW and b = nearer to the downstream monitoring point					

The raw water source supplying the mains was transported from an upland surface reservoir and treated with a ferric coagulation. Figure 37 shows seasonal trends of treated water parameters which could affect accumulation rates. Total organic carbon (TOC), water temperature and metal concentrations (Fe, Al and Mn) values were collected from January 2013 to May 2017 through scheduled discrete sampling. From Figure 37, it can be observed that higher inorganic (Fe and Al) and organic (TOC) content was found in the treated water during the warmer months indicating higher bulk water loading during the summer season. Manganese concentrations, however, did not appear to demonstrate seasonal variation.

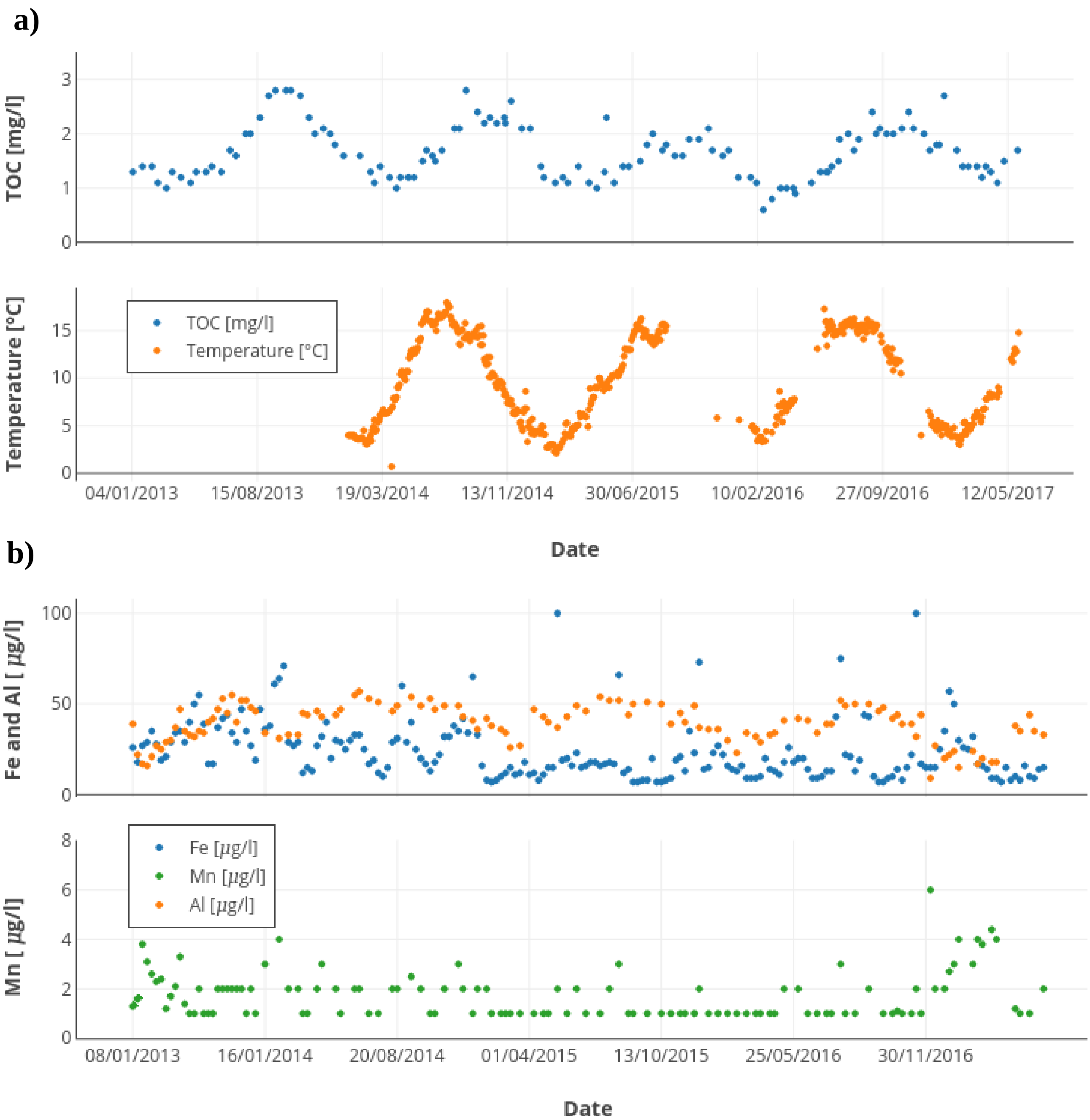


Figure 37: WTW treated water discrete samples collected from January 2013 to May 2017 a) TOC in mg/l (top) and temperature in °C (bottom), b) Fe, and Al concentration in µg/l (top) and Mn concentration in µg/l (bottom)

7.5.3 Network hydraulic comparisons

The trunk mains were selected to fit site selection criteria requiring similar hydraulic performance. Figure 38 presents a sample of the trunk mains long-term measured flow, velocity, shear stress, Reynold number and pressure, highlighting compliance with the selection criteria. Comparing pressure amongst the test trunk mains has been added for completeness as identified as not associated with discolouration process.

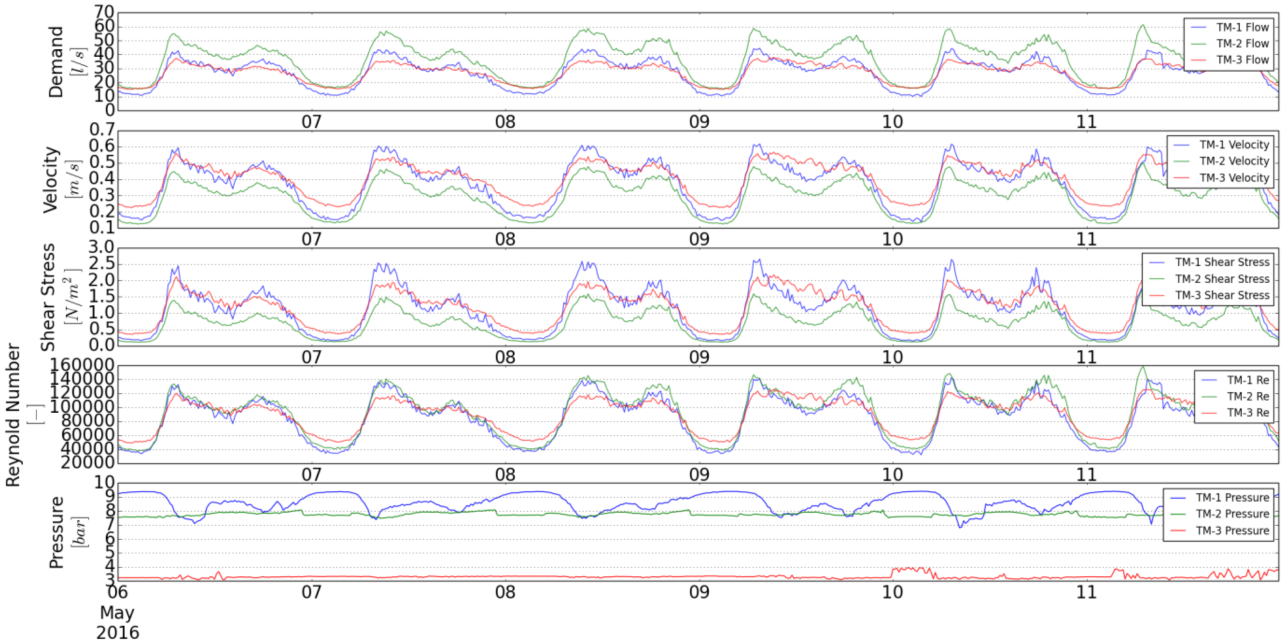


Figure 38: Three trial trunk main hydraulic profiles. From top to bottom; demand [l/s], velocity [m/s], shear stress [N/m^2], Reynold number [-] and pressure [bar]

7.5.4 Data monitoring

Trunk main turnover with the highest flow conditioning was approximately 3.5 hour. Due to the long turnover, a 15-minute sampling resolution was accepted as appropriate for flow conditioning trials. Continuous data (both flow and turbidity) was measured at a 15-minute sampling frequency to maintain consistency with trial data. The trial flow increases delivering the targeted excess shear stress was monitored and controlled by specially designed Langham hydrant standpipe with electromagnetic ABB Aquamaster 3 flow meter (www.abb.com) with an accuracy of ±5% of reading and maximum working pressure of 12 bar. Turbidity responses during flow conditioning were measured by ATI Nephnet logger (www.atiuk.com). The ATI Nephnet logger used an infrared (IR) Nephelometric measurement process and the functioning range was set for 0-4.0 NTU with an accuracy of ±5% of reading. Trial duration turbidity data was spot checked with a 2100Q Hach handheld logger (www.hach.com) which was calibrated with standard formazin dilution sample. The handheld logger was calibrated for 0-100.0 NTU with an accuracy of ±2% of reading.

Aquamaster 3 flow meters were installed at the inlet of each trunk main prior to the investigation for capturing long-term data. For measuring treated water turbidity, Sigrist Aquascat 2 WTM turbidity meter (www.photometer.com) was pre-deployed at the treatment outlet. The turbidity instrument used IR Nephelometric measurement process, and operating range was 0-4.0 NTU with reading of ±0.001 NTU. To capture any unplanned event (e.g. burst) turbidity response, downstream continuous turbidity data was monitored from October 2015 to February 2016 using the ATI NephNet turbidity logger. During this time, ATI loggers range set for 0-4.0 NTU. After February 2016, Evoqua Hydraclam loggers (www.evoqua.com) were deployed which used the same IR Nephelometric measurement procedure. The instruments range was set for 0-10.0 NTU with an accuracy of ±5% of reading. All loggers calibrated with standard formazine sample. Continuous data was also spot checked regularly by Hach handheld logger to ensure consistency with trial monitoring.

To calibrate pipe roughness, one-off 24 hour downstream pressure prior investigation was measured using Transientminder (www.syrinix.com) at 15-minute sampling frequency for the three trunk mains. The Syrinix pressure logger range defined for 0-20 bar with an accuracy of 0.1% of full-scale output. Figure 39 shows typical flow conditioning operational setup with monitoring equipment.

Figure 39: Monitoring during flow conditioning trials with two ATI NephNet turbidity loggers (orange boxes) and ABB flow meter attached with Langham UK standard standpipe

7.5.5 Fieldwork procedure and timeline

Flow conditioning trials were designed not to exceed 1.0 NTU responses to minimise discolouration risk on downstream consumers. The PODDS model (Boxall and Saul, 2005) was used to design shear stress steps with a 1.0 NTU constraint using previously calibrated model parameters from similar networks. From modelling assessment, TM-1 was designed with a 40% shear stress increase above the peak shear stress for all trials and applied at quarterly intervals. Maximum 40% additional shear stress was selected based on the WTW hydraulic capacity and trial specific drainage conditions. TM-2 had 40% shear stress increase above the peak shear for initial (time zero) and final trial (12 month) and 15% shear increase at quarterly intervals. TM-3 was designed as a control with no interventions for 12 months and only the 40% shear stress increase above the peak for initial and final trial assessment (see Figure 35). All flow conditioning trials were operated under similar conditions, i.e. same time of day and using the same equipment to maintain trial and data consistency.

As the test trunk mains were demand driven and with diurnal flow patterns, target excess shear stress increments were achieved during the morning (about 7:30-8:00 am) peak period when the network had the highest demand and lowest pressure. Morning peak demand period was chosen to increase shear stress as it requires the lowest additional demand.

7.5.6 Data processing: Long-term monitoring

Due to discolouration particles cohesive properties (Boxall et al., 2001), optic lens fouling can occur causing drift in measurement over time (Gaffney and Boult, 2012). To reduce drift effect, ATI Nephnet logger lens was cleaned on site bi-weekly during its deployment period (From October 2015 to February 2016) with little or no drift observed and showed good agreement with spot checks. The Hydraclam turbidity logger was deployed after February 2016 where drift was adjusted using the patented “Evoqua” post-processing algorithm which demonstrated good agreement with on-site bi-weekly handheld spot checks. The Aquascat 2 WTM turbidity logger maintenance was conducted regularly as part of regulatory work and hence, no significant drift was found from turbidity signals.

ATI measured turbidity signal data had relatively less noise with standard deviation (SD) of 0.03 (sample size, $n \geq 5800$) compared to Hydraclam (SD=0.38) for same sample size. The ATI logger measured data as at continuous sampling flow at 0.02 l/s (~1.2 l/m). Hydraclam logger uses a purge system at each 15-minute before sampling that was limited to total discharging volume of 6l at 0.1 l/s flow rate, due to local drainage constraints. This is thought to have resulting noise in the data due to incomplete purging of the hydrant riser and connecting pipe work. A moving average to measured data was applied to minimise this noise. Different rolling means were investigated and 1-hour was selected based on minimising the signal noise yet retaining the measured behaviour. Figure 40 shows a rolling mean sensitivity study comparing part of measured turbidity response of TM-2. It is noted that turbidity responses measured during the planned trials are not included in the filtering process as the higher and constant flows through hydrant avoided any riser turnover effect.

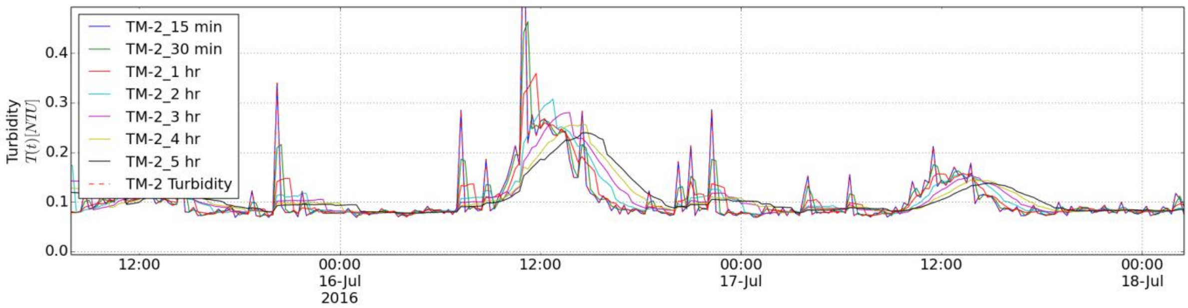


Figure 40: Part of measured turbidity response of TM-2 with rolling mean sensitivity analysis

7.5.7 VCD modelling process for the investigated trunk main

It was anticipated that the trunk main with the highest magnitude imposed shear stress and more frequent event would produce the highest number of notable turbidity responses. Therefore, calibration of TM-1 was planned first to assess the VCD model simulation performance.

Prior to the VCD simulation, all trunk main models were hydraulically calibrated to ensure accurate hydraulic and water quality model representation. The pipe roughness (k_s) boundary condition was determined from pressure difference, and internal diameter (ID) was estimated from the (Boxall et al., 2004) concept of 1 mm k_s reduces 2 mm effective ID. The parameter boundary condition was facilitated in the PEST calibration software (Doherty, 2005) in conjunction with EPANET (Rossman, 2000) model to identify unique paired (k_s and ID) values for VCD simulation where calibrated ID was constrained by the industry record effective ID. Zero leakage was considered for hydraulic calibration. Table 10 presents the trunk mains optimised hydraulic properties.

Table 10: Trunk mains calibrated hydraulic properties

Trunk main system	Optimised internal pipe diameter, ID [mm]	Optimised roughness, k_s [mm]	Modelled length [km]
TM- 1	303.2	8.50	6.4
TM-2	395.8	10.35	5.6
TM- 3	292.3	7.50	5.9

As this is the first attempt to calibrate long-term flow-turbidity time series data, a modeller intuitive approach was used to facilitate the calibration and hence a manual parameter search exploration was used for calibration. The manual calibration was undertaken by tuning three model parameters ($\beta_{r,}$ $\beta_{e,}$ α) with initial values extrapolated from the previous findings (Furnass, 2015; Furnass et al., 2014). The calibration was undertaken by single extended period simulations using a single set of parameters to assess the model parameter functionality and discolouration processes facilitate in the model correctly. To assess the quality of model prediction, simulated response compared with downstream flow event induced turbidity measurements. The model fitting quality was assessed by Nash–Sutcliffe Efficiency (NSE) coefficient metric (Nash and Sutcliffe, 1970). The NSE method is widely used to describe both hydraulic and hydrological model performance and shows the model fitting quality relative to the average of measured data. Since NSE is sensitive to the outliers and average values, NSE assessment was performed for both +12 months measured data and event induced turbidity data to outline the model performance towards any hydraulic changes.

Turbidity at the downstream end is a function of both material release from pipe wall and incoming turbidity from upstream network. In this case, upstream is the WTW where water was not particle free. Hence measured treated water turbidity was used to model for upstream material flux.

In addition to the three model parameters optimisation, initial material layer strength profile needs to be determined to reduce simulation uncertainty. The amount of material $\varphi(\tau,t)$ at t=0 depends on the combined effect of material mobilisation and accumulation process due to the ongoing imposed shear stress conditions. Due to wall state unknown starting conditions, all models were simulated assuming the maximum amount of material (φ=1.0) initially present on the pipe wall. While this process caused initial high over predictions, after a period it converges to a realistic state. To minimise any over prediction effect and to develop a realistic wall state condition, all models were simulated with varying period of measured shear stress data prior to the monitoring period and check if any impact was observed in NSE values. From this assessment, nine months measured shear stress data prior to the investigation period was found enough to minimise any effect on the model output. It is to be noted that these simulation results were not used for any calibration.

To allow tracking of discolouration material content, the VCD model discretises the shear stress range into independent bands. The selection of how many tracked shear strength layers to produce accurate simulation is important as picking up large numbers could be computationally ineffective. To identify the suitable number of discretely tracked layers for this study, sensitivity analysis of numbers of strength bands of TM-1 plotted with model fitting performance (NSE) and computational times are shown in Figure 41. TM-1 data was selected as this has the highest number of calibration point with notable turbidity response. The sensitivity analysis simulation was conducted with initial best guess parameter values of TM-1 and then repeated with the final calibrated values with no changes to overall findings. The sensitivity study shows that 20 or above τ bands produced a lower error metric (higher NSE) for the studied trunk main with no observable change in computational time. To ensure accuracy at this stage, a more conservative approach was adopted by tracking 100 discrete strength bands.

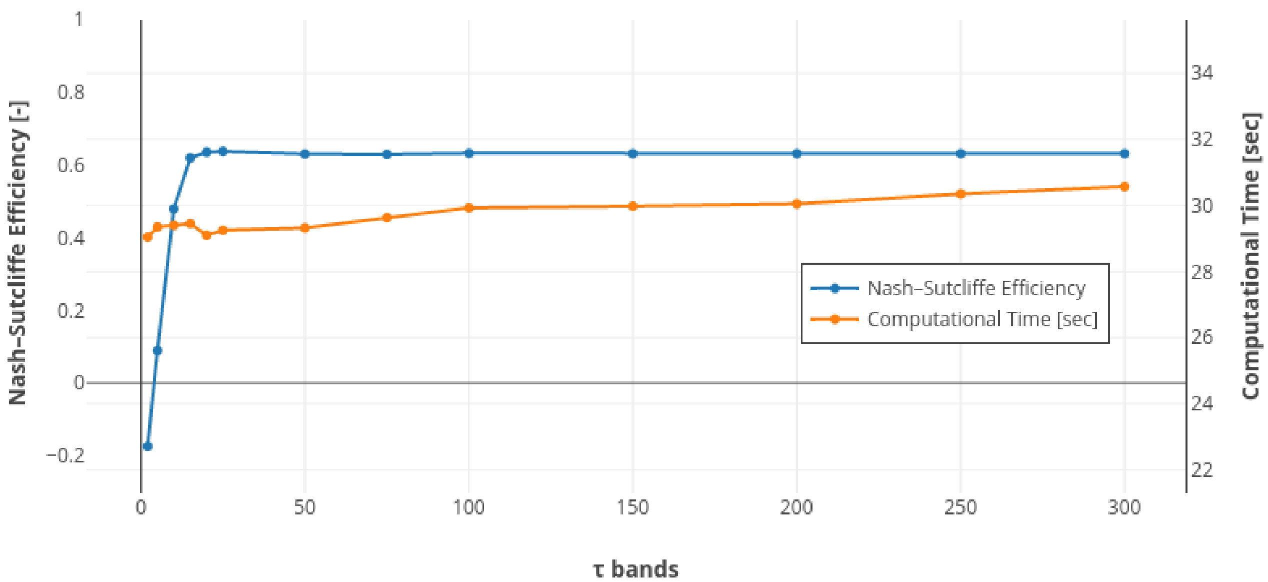


Figure 41: Sensitivity analysis of model calibration quality in NSE value (unit less) and associated computational time (seconds) to determine the suitable τ bands for model simulation

7.6 Results

7.6.1 Long-Term data monitoring

Figure 42 shows the long-term (+12 months) measured common upstream treated water turbidity and flow and downstream turbidity for each trunk main. Figure 42 y-axis turbidity scales are clipped to 0-1.0 NTU to aid visual interpretation of main features of interest. While all the flow conditioning trials were initially planned to undertake at similar times, TM-3 trials started later due to operational constraints. The data shows that treated water turbidity lies between 0.05-0.2 NTU and other water quality parameters e.g. metals are within regulatory limit (see Figure 37) indicating a consistent high-quality water exiting from the treatment works.

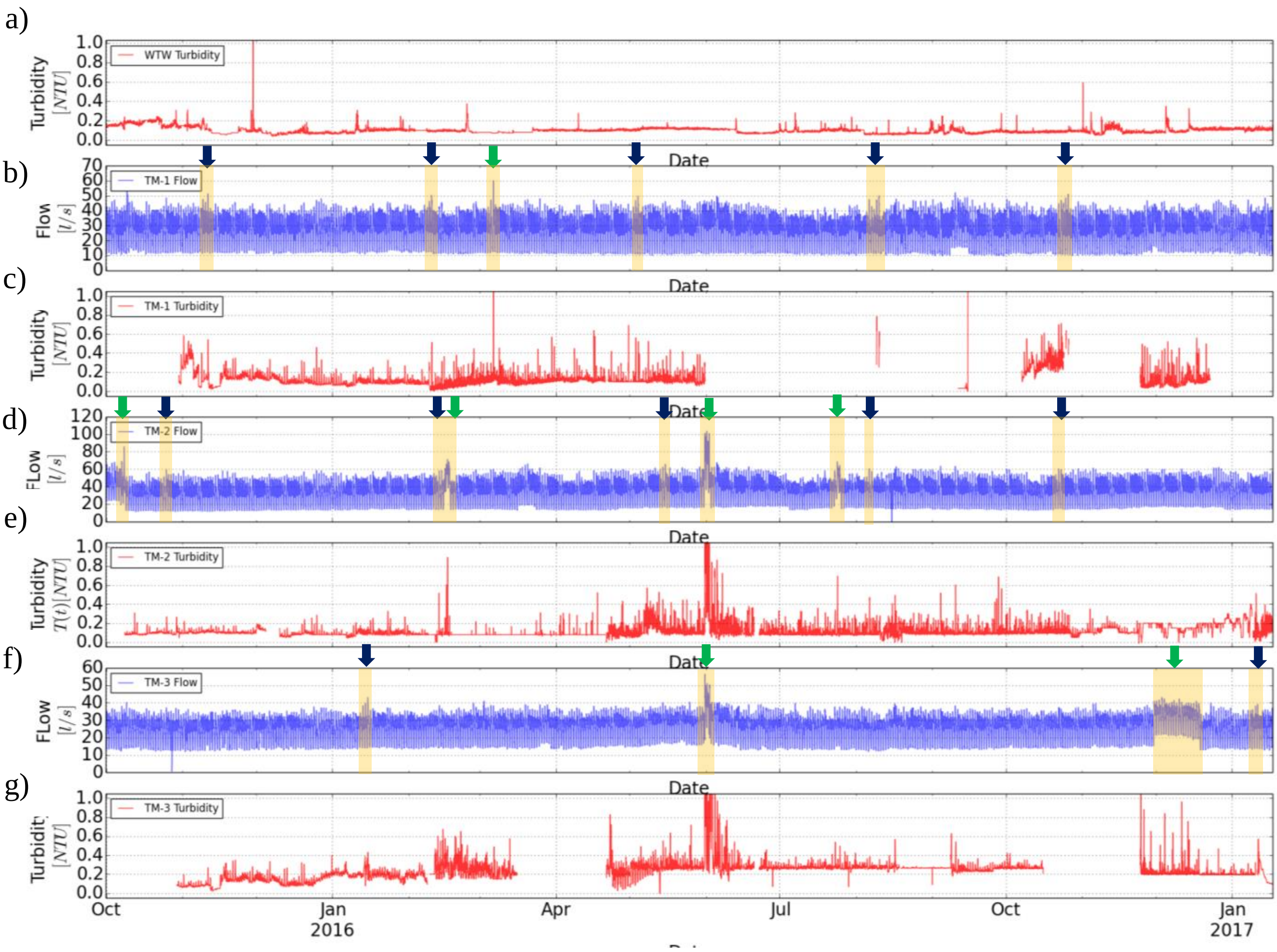
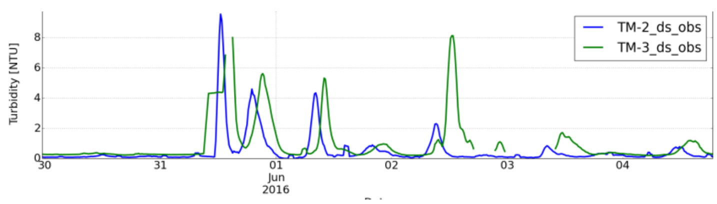


Figure 42: Continuous flow and turbidity measured response from WTW outlet (top) and three trunk mains from October 2015 to January 2017. Continuous data in red is the measured turbidity, and flow data in blue. Turbidity response is clipped to 0-1.0 NTU in y-axis for better visibility. Dark blue arrows represent flow conditioning trials and green arrows unplanned burst events with highlighting

the section of interested data. a) Treated water turbidity, b) TM-1 flow, c) TM-1 turbidity, d) TM-2 flow, e) TM-2 turbidity, f) TM-3 flow and g)TM-3 turbidity.

The flow profile of each trunk main shows diurnal patterns and a sub-daily variation existed in each trunk main system. During the investigation period, a number of burst events took place. All reported unplanned hydraulic events, as indicated in Figure 42, were cross-validated with water company repair and customer contacts records. All of the events occurred in the downstream distribution zones, except the event on TM-2 and TM-3 recorded at the end of May and into early June 2016. This event started in TM-3 on 31st May 2016 about 1.3 km from the WTW outlet. Due to the operational repair work, TM-3 demand was rezoned via TM-2 from a further 0.4 km downstream distance, which initiated the TM-2 event. Figure 43 shows the measured turbidity response during the event for both TM-2 and TM-3 and network rezoning schematics for repair work. Measured shear stress event of TM-3 in December 2016 was a leak of 6 l/s occurring about 2 km distance from the WTW outlet.

a)



b)

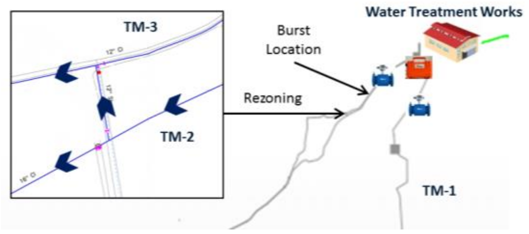


Figure 43: Burst induced turbidity response and rezoning operation: a) Burst event produced downstream turbidity response of both TM-2 and TM-3, b) Network schematic with approximate burst location and rerouting operation

7.6.2 VCD model validation

7.6.2.1 Trunk main 1

Figure 44 presents the TM-1 VCD model calibration results including applied shear stress and associated simulated and measured turbidity responses from January 2015 to January 2017. TM-1 was the normal flow conditioning main where the first nine months (January to September 2015) shear stress profile was used to simulate the model initial wall state conditions starting at φ=1.0. As expected the model overpredicts the initial turbidity response, as shown in Figure 44. However, this was necessary to build confidence in the simulated wall state conditions and therefore not considered in the evaluation of model fitting process. The model was calibrated for the +12 months data set (from October 2015 to January 2017) as shown in Figure 44 with a single simulation and one calibrated parameter set. Only the notable turbidity responses produced from the planned flow conditioning and unplanned burst events was used for the calibration with minimisation of the dissimilarities between measured and simulated response by NSE correlation metric. The NSE value showed that model simulated the +12 months measured data overall with good accuracy with an NSE value of 0.61. The NSE for each planned trial and unplanned event calibration are summarised in table 11 with the results indicating high accuracy simulation.

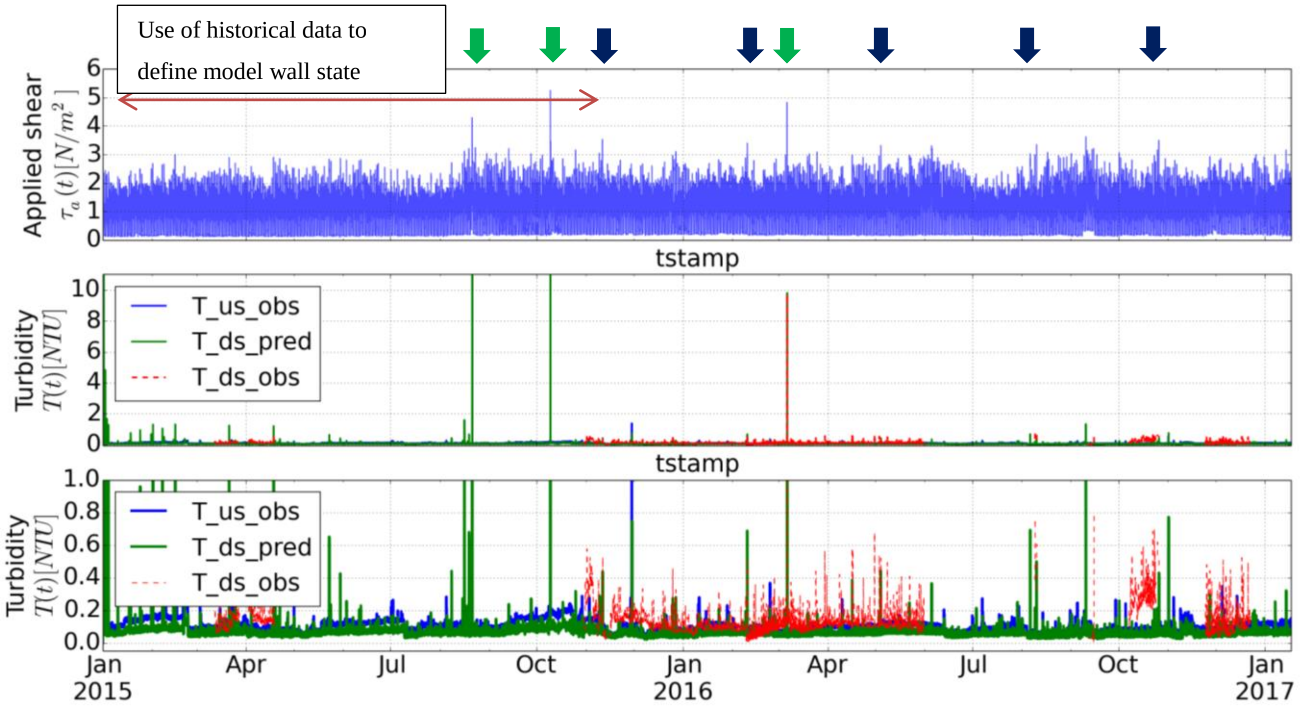


Figure 44: TM-1 VCD model calibration results of 24 months where first nine months data was used to develop initial wall state condition. Top plot: Long-term shear stress profile in N/m2 (where green arrow showing burst events and blue for flow conditioning events), middle and bottom plot: showing downstream simulated turbidity (T_ds_pred), observed upstream turbidity ((T_us_obs) and downstream turbidity (T_ds_obs). Bottom plot shows turbidity profile in scale of 0-1.0 NTU in y-axis scale for better data visibility

Table 11: TM-1 NSE model calibration results from hydraulic events highlighted in Figure 44 from left to right direction

Calibration Point	Total [+12 months]	Trial 1	Trial 2	Burst in March 2016	Trial 3	Trial 4	Trial 5
NSE (-)	0.62	0.78	0.63	0.96	0.79	0.80	0.86

Figure 45 presents flow conditioning and burst event measured and simulated turbidity from TM-1. Figure 45(a) shows that about 0.5 NTU measured turbidity response was simulated successfully with slight under predictions by the VCD model with an increase of imposed shear up to 3.5 N/m^2. After three months (February 2016) interval, the network accumulated enough material to cause a 0.45 NTU turbidity responses due to the 3.5 N/m^2 imposed shear event which shows slight over VCD model prediction in Figure 45(b). Figure 45(c) presents the burst event in TM-1 that occurred in March 2016 where shear stress increased rapidly up to 5.0 N/m^2 for about 2.0 hours, and a 10.0 NTU response was measured. The observed 10.0 NTU response was simulated correctly by the VCD model. With a shorter accumulation period after the burst, Figure 45(d) presents the conditioning event in May 2016 that produced a turbidity response of 0.5 NTU which was simulated effectively by the VCD model. Figure 45(e) and 45(f) demonstrate the VCD model effectively simulated the flow conditioning event response undertaken in August and October 2016. The simulation results for all planned and unplanned events from Figure 44 show the model simulated peak measured turbidity with an average accuracy of ±0.2 NTU. Simulation results in Figure 44 also predict about +12.0 NTU responses during the burst events in August and October 2015. However, it is not possible to confirm as no turbidity measurements were obtained during this period and the model may be influenced by initial fully developed material layer conditions.

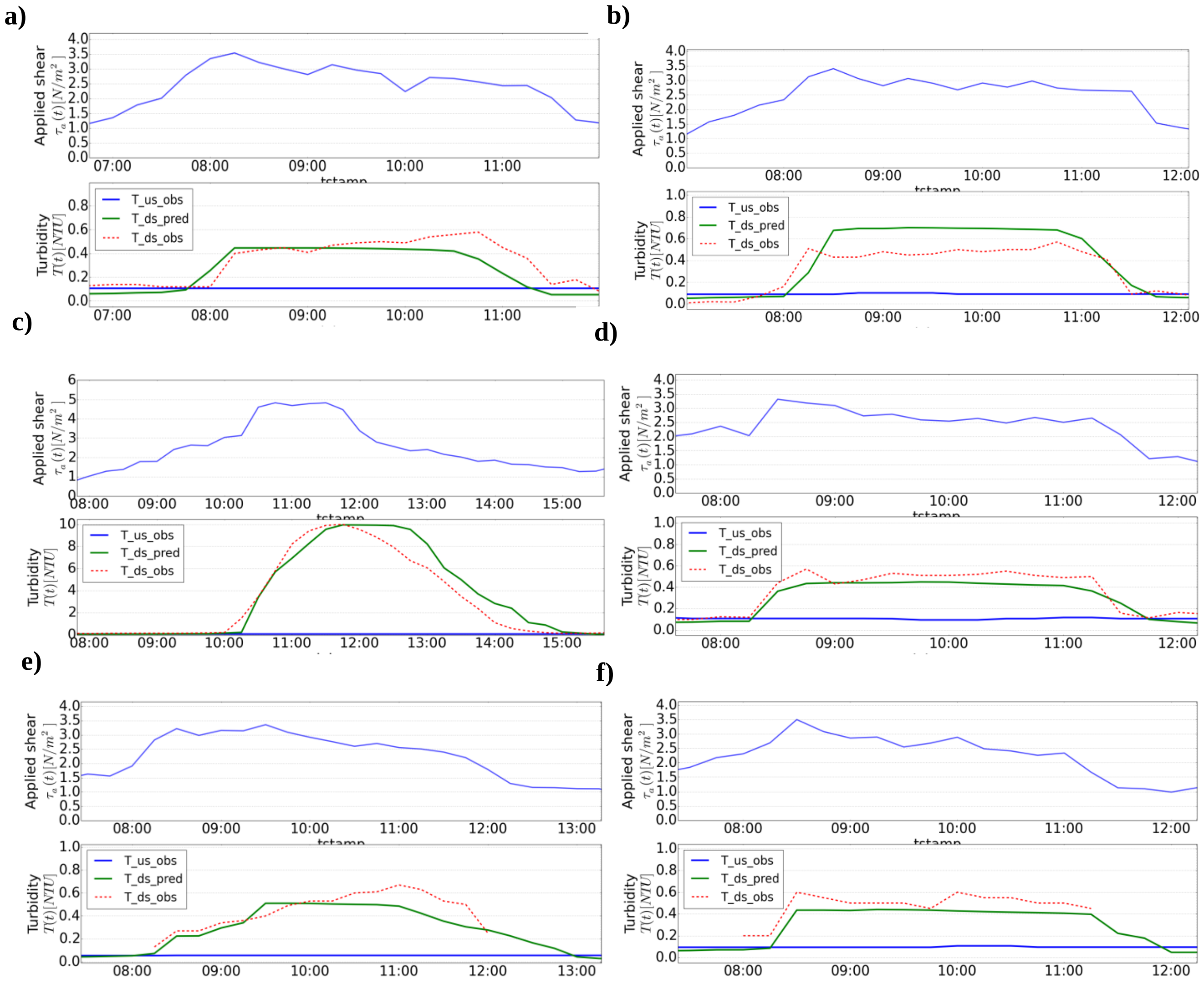


Figure 45: TM-1 flow conditioning trial response and associated VCD model simulation results present with a single simulation and fixed set parameters. Events Figure are shown from left to right of the +12 months flow-turbidity time series. a) trial 1 b) trial 2 c) burst in March 2016 d) trial 3 e) trial 4 f) trial 5. Here top plot shows imposed shear stress in N/m^2 and bottom plot modelled and measured turbidity response in NTU

7.6.2.2 Trunk main 2

The VCD model mobilisation and accumulation functionality were further validated for TM-2 measured data using the parameter values found for TM-1 as initial values. Figure 46 shows the applied shear stress of TM-2 from October 2015 till January 2017 including upstream-downstream measured turbidity and simulated turbidity response using a single set of calibrated parameters with a single run simulation. As with TM-1, the TM-2 model was initialised using shear stress data from January 2015 till September 2015, not shown in Figure 46. The layer equilibrium effect of TM-2 was similar to TM-1 with the expected initial over predictions.

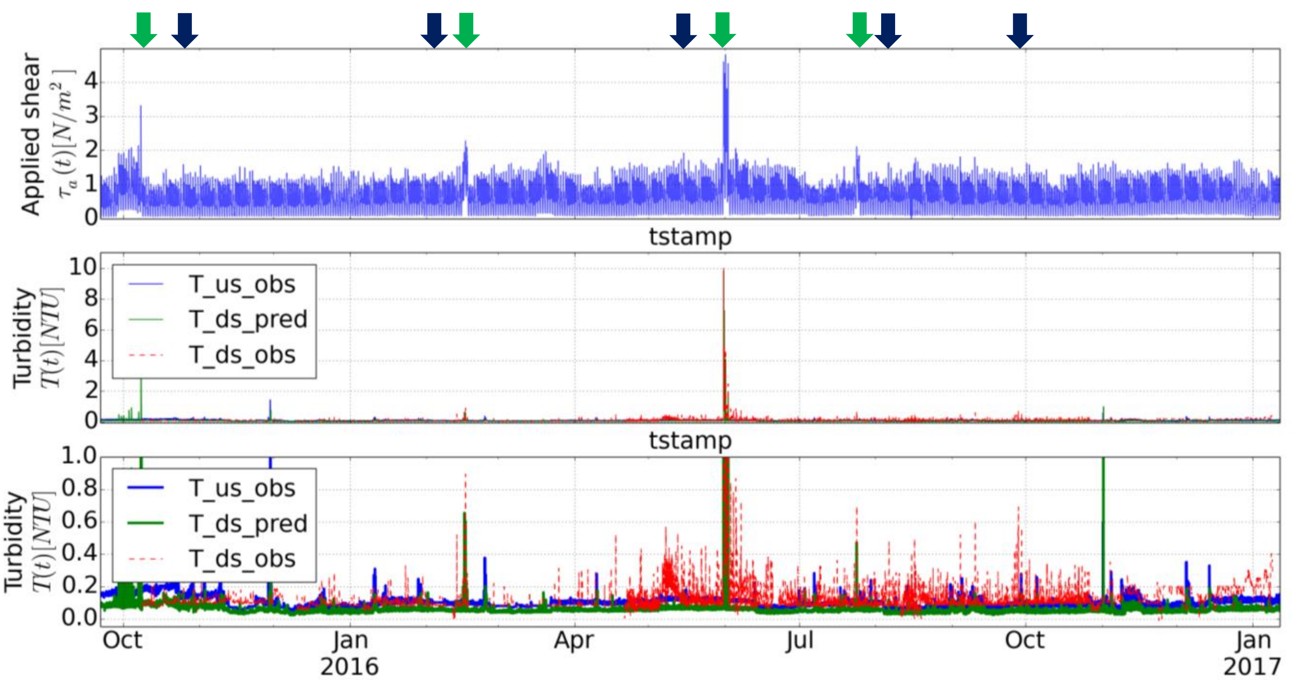


Figure 46: TM-2 VCD model calibration results from October 2015 to January 2017. Top plot: Long-term shear stress profile in N/m2 (where green arrows show burst events and blue arrows flow conditioning events), middle and bottom plot: downstream simulated turbidity (T_ds_pred), observed upstream turbidity (T_us_obs) and downstream turbidity (T_ds_obs). The bottom plot shows turbidity profile in the scale of 0-1.0 NTU in y-axis scale for better data visibility.

TM-2 was the passive flow conditioning main with lower quarterly imposed shear stress events. Several large bursts events, much higher than planned trials were recorded during the monitoring period. As a result of the bursts effect on material condition, none of the planned event turbidity responses were measured above background turbidity response. Only the bursts with notable turbidity responses were therefore used for testing VCD model simulation performance. As with TM-1 calibration, a manual search technique was applied, and quality of fitting was measured by NSE coefficient. While the overall calibration of +12 months data presented in table 12 indicates a satisfactory NSE value of 0.44, average NSE values for burst induced responses are 0.77, indicating high-quality calibrations for the arguably more important event periods.

Table 12: TM-2 NSE model calibration results from hydraulic events highlighted in Figure 46 from left to right direction

Calibration Point	Total [+12 months]	Burst in February 2016	Burst in June 2016	Burst in July 2016
NSE (-)	0.44	0.81	0.80	0.75

Figure 47 shows the burst events responses and associated single run VCD model simulation from Figure 46. Figure 47(a) shows the VCD model simulated well with slight under-prediction of the event in February 2016 where maximum measured turbidity response was 0.8 NTU. Figure 47(b) and 47(c) show the model simulation to the measured response of events occurring in June and July 2016. The burst event in early June 2016 was initiated during the rezoning process where shear stress was increased up to 4.4 N/m^2 (normal prevailing shear stress was 1.5 N/m^2). Both the flow meter and turbidity logger captured the event effectively. The event continued for 60 hours duration and each increase in shear stress caused further material release with turbidity recorded at a maximum of 10.0 NTU. The calibration figure shows that the model achieved good simulation of data. Another burst event was recorded at the end of July 2016 as shown in Figure 47(c) where simulated response fitted well to the measured 0.7 NTU turbidity with slight underprediction. The simulation results for the burst event show model simulated maximum turbidity response within an average accuracy of ±0.3 NTU, indicating good quality calibration.

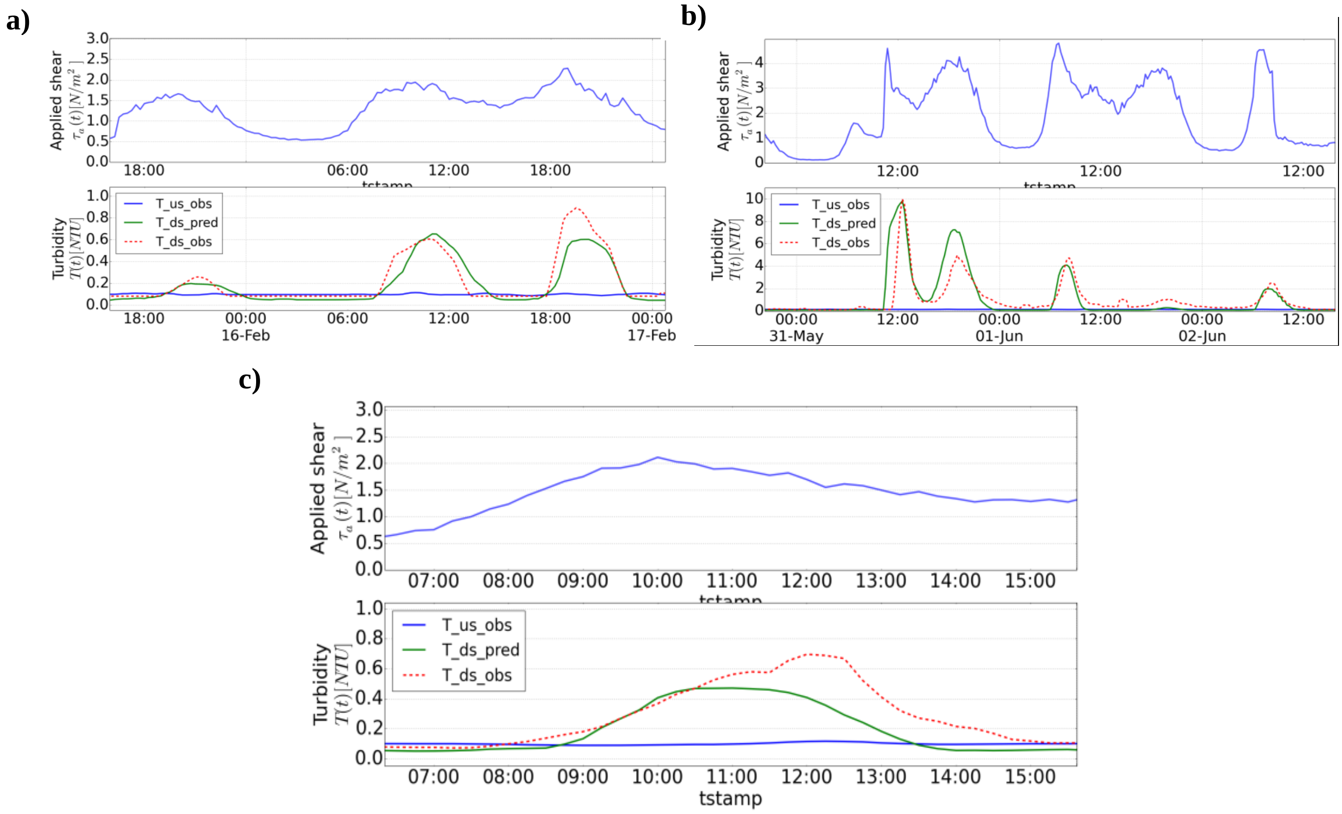


Figure 47: TM-2 flow conditioning event measured and single run VCD model simulation results. a) Burst in February 2016, b) burst in May-June 2016 c) burst in July 2016. For each figure, top plot shows applied shear [N/m^2], and bottom plot is the modelled and measured turbidity response [NTU].

7.6.2.3 Trunk main 3

The model mobilisation and accumulation processes were further tested for TM-3, assigned as a control network. Figure 45 shows the TM-3 single simulation calibration of +12 months dataset using the parameter values found for TM-1 and TM-2 as a starting point. As previously, the model was initially run for nine months (January 2015 to September 2015) to develop material layer conditions. TM-3 had only two planned events (see Figure 35) with a 12-month interval. In addition, two burst events were recorded in June and December 2016. No significant turbidity response was measured from the burst in December 2016 event due to its low magnitude and location at the upstream point and planned trial in January 2017 resulting from the pressure constrained PRV settings. Therefore, only the planned trial in January 2016 and burst event in June 2016 was used for model calibration. The model simulated the shear stress events in January 2016 and June 2016 well and with high accuracy. Table 13 summarises the model simulation performance results in NSE values.

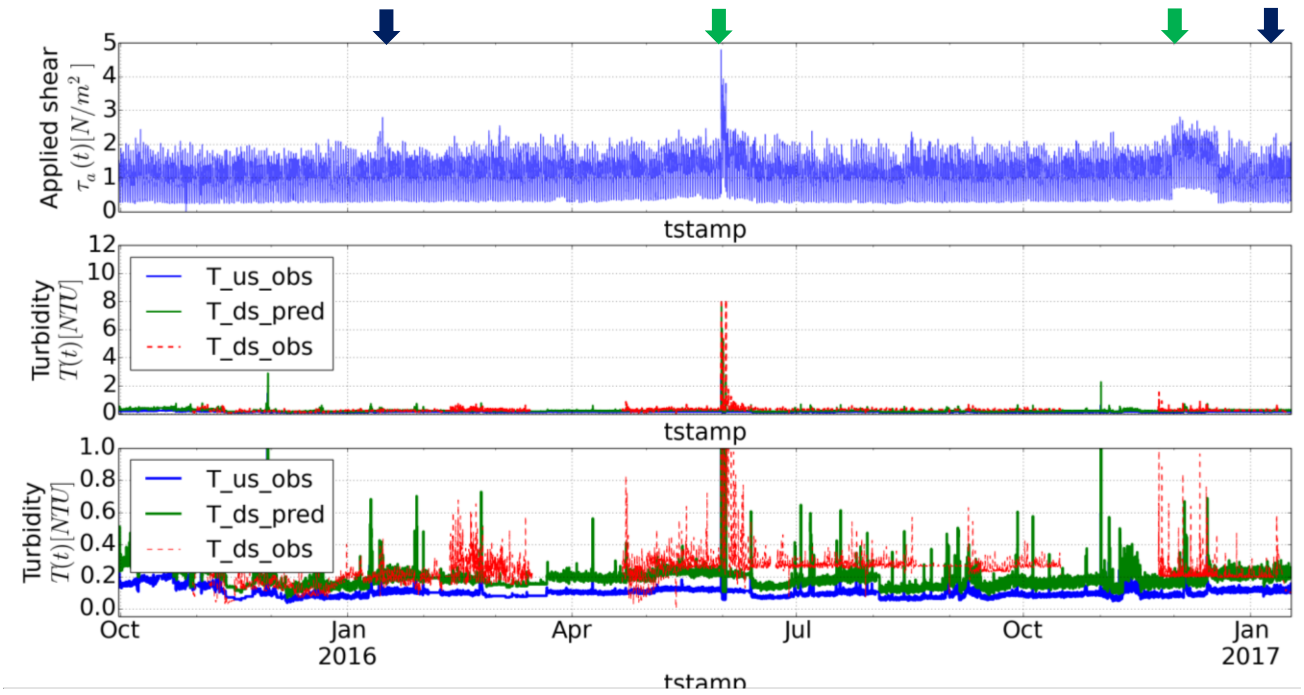


Figure 48: TM-3 VCD model calibration results from October 2015 to January 2017. Top plot: Long-term shear stress profile in N/m^2 (where green marks showing bursts event and dark blue for flow conditioning event), middle and bottom plot showing downstream simulated turbidity (T_ds_pred), observed upstream turbidity (T_us_obs) and downstream turbidity (T_ds_obs). Bottom plot is showing in scale of 0-1.0 NTU in y-axis scale for better data visibility

Table 13: TM-2 NSE model calibration results from hydraulic events highlighted in Figure 48 from left to right direction

Calibration Point	Total [+12 months]	Trial in January 2016	Burst in June 2016
NSE (-)	0.24	0.91	0.78

Figure 49(a) shows the model simulation to measured turbidity in January 2016 where 0.45 NTU turbidity was observed during the trial. As TM-3 demand was rezoned through TM-2 during the burst event in June 2016, upstream mass flux was modelled from the TM-2 simulation response at 1.7 km length. The TM-2 average daily flow was then subtracted from the actual metered burst data and used for TM-3 simulation. Figure 49(b) shows the calibration during the burst event in June 2016 where the model simulated the measured turbidity response well. The last turbidity spike of 8.0 NTU was not well simulated by the model, although it was unclear why there was such a high spike at the end of the burst event even with relatively low measured shear stress. Overall, with the exclusion of unknown turbidity spike, the model simulated the peak turbidity response within ±0.2 NTU accuracy.

a) **b)**

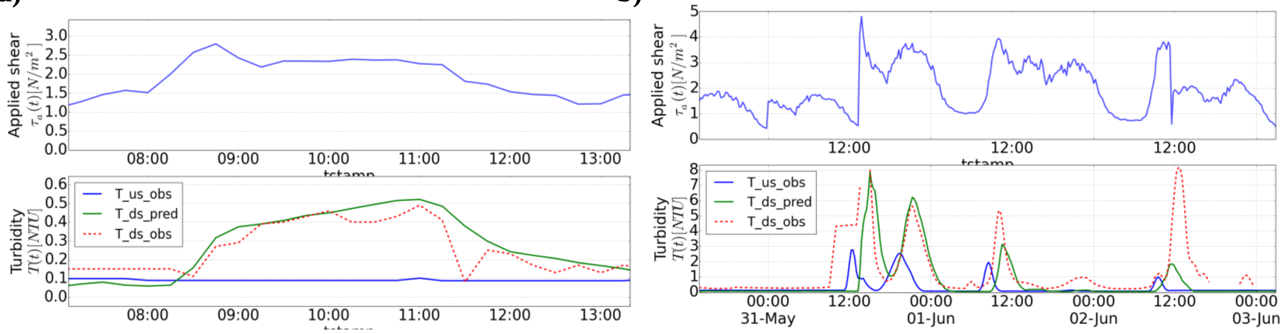


Figure 49: TM-3 hydraulic event single run simulation a) Flow conditioning in January 2016 b) burst in May-June 2016. Top plot shows applied shear in N/m^2 and bottom plot is the modelled and measured turbidity response in NTU

7.6.3 Accumulation rate

The VCD model calibration results indicate the accumulation rate was similar in all three trunk mains, supporting the conceptual approach advocated at the trial outset when selecting the trunk mains. The optimised accumulation rate for all three trunk mains was found to be between 1.65 to

1.85 years. This means in operation it would take 1.65-1.85 years to fully regenerate material layers starting from a totally clean condition if no further mobilisation occurred with the current hydraulic configuration and bulk water quality. The lowest accumulation return interval was found in TM-1 of 1.85 years which is a partially lined main. TM-2 accumulation return interval was 1.65 years and TM-3 was 1.7 years, both mains unlined CI.

7.6.4 Seasonal variation in accumulation rates

It was conceptualised from previous research that the accumulation rate may show seasonal variation due to temperature influences on microbial and chemical processes. To explore seasonal variation in accumulation rate (β_r), the model was calibrated using each quarterly measured period by changing β_r while mobilisation parameters (β_e, α) were held constant which is only possible for TM1 that had events in all quarters. Resulting parameter and NSE values are given in Table 14. It should be noted that β_r was assumed null during the first planned trial response as there was no previous event induced response point available.

Quarterly calibration results predict that β_r was higher during the colder months (material takes longer to accumulate) and lower in warmer periods of the year. For TM-1 the β_r values range was varied from 1.6 to 2.7 years with temperature ranging from 4 to 15°C. The highest accumulation period of TM-1 was calibrated at 2.7 years when the average treated water temperature was 4°C. There were limited numbers of β_r calibration points available for TM-2 and TM-3. For both TM-2 and TM-3, there was no cold period calibration available and rest calibration period was similar to the TM-1. The final calibrated β_r was predicted between 1.65-1.85 years which is closer to the lower accumulation rate (influenced by higher temperature).

Table 14: Seasonal effect on VCD model accumulation rate parameter

Calibrated Parameters and water temperature	**Initial [FC1]**	**0-3 months [FC2]**	**3-6 months [FC3]**	**6-9 months [FC4]**	**9-12 months [FC5]**	**0-12 months**
TM-1 β_r [years]	-	2.8	1.75	1.60	1.65	1.85
NSE [-]	-	0.97	0.92	0.98	0.97	0.61
Average treated water temperature [°C]	10	4*	8*	15	13	-
*Temperature data was determined from linear rolling mean analysis using Figure 37(a) temperature data						

7.7 Discussion

7.7.1 VCD model calibration analysis

This paper presents for the first time simulation of long-term turbidity behaviour due to the hydraulic changes in large diameter trunk mains using the VCD model material tracking facility. The calibration results show that the model successfully simulated the turbidity behaviour by tracking continual material mobilisation and accumulation across a range of layer strengths defined within the trial methodology. For this study, the model simulated peak turbidity response for both planned and unplanned shear stress events that was within an average accuracy of ±0.25 NTU with high NSE value, and is the first model to simulate accumulation processes. The simulation performance suggests that the model correctly describes accumulation processes over varying strength layers and hence discolouration behaviour at any given time. While the weak layers can mobilise during the hydraulic events, stronger material can accumulate at the same time, suggesting non-linear complex conditions exist on the pipe wall. The calibration results suggests that continual material mobilisation and accumulation behaviour in this case describe the more realistic accumulation processes for estimating the relative amount of material present on the pipe wall at any given time period. It is to be noted that if accumulation rate was incorrect, mobilisation would have not been modelled well.

The confidence in accumulation behaviour was further confirmed by calibrating the model to both relatively low imposed shear stress (planned flow conditioning) and high imposed shear stress events (unplanned burst). This was achieved successfully for all three trunk mains where the model had to track a range of varying strength cohesive layers. The successful calibration of both planned and unplanned hydraulic events data with high accuracy for the three trunk mains validates that discolouration causing material layers have a range of strength bands and accumulation occurs simultaneously across all shear strengths. The optimisation result also validates model mobilisation, with accumulation functionality implemented correctly in the software to simulate long-term turbidity behaviour.

For this study model calibration was conducted by a manual search process. The VCD model calibrates three empirical parameters, using both mobilisation and accumulation processes, making it relatively easier to calibrate than its predecessor PODDS model, which has four parameters and simulates only the mobilisation processes. While the manual search calibration cannot guarantee global minima or unique solutions with reduced parameter uncertainty, the parameter transferability found in the three trunk mains provides confidence in model optimisation. An automatic calibration process could be used to facilitate optimisation, although care is required to avoid over sensitivity towards outliers or background turbidity response during calibration.

The study shows the scope of the single pipe length model provides good simulation accuracy without any need for use of a complex mass transport model, e.g. EPANET (Rossman, 2000). Typically the trunk main has few take-offs and connections and changes of hydraulic or water quality conditions in its running length. These changes in hydraulic or water quality conditions can be modelled as a series of pipe connections. The model output at downstream can be used to simulate the upstream conditions of the next or following pipe, as was done for the TM-3 June 2016 burst event. Since this is a single pipe length model, it does not require any storage mixing sub-models, e.g. trunk main to service reservoir, to characterise discolouration material conditions, which likely reduces modelling complexity.

7.7.2 Accumulation rate assessment

The accumulation rate parameter (β_r) values from calibration results were found to be similar in all three trunk mains. The final calibration results were also similar for the mobilisation rate (β_e) and material release coefficient (α), although not published due to the intellectual property rights agreed with the water company funding the work. The simulated accumulation return interval for the three trunk mains (1.65-1.85 years) was comparable with the previous field accumulation return interval investigation which was found between 1.5 to 4 years (Husband and Boxall, 2011) and within 1.5 years (Vreeburg et al., 2008). While the previous studies found accumulation rates from mass-balance analysis, this study found similar rates through model fitting to measured response simulating both material mobilisation and accumulation processes. Even though the procedure for estimating accumulation rates was different, accumulation rate ranges from both methods was similar giving the confidence in β_r findings through the VCD model and suggesting model parameters can be transferable for future calibration use.

Similar βr found for the three trunk mains with varying imposed shear stress events evident that accumulation rate per shear strength was not a function of a degree of imposed event and risk remain at relatively low shear event same irrespective of intervention conditions. While not removing the stronger layers via flow conditioning trial may lead to the weaker layer accumulating more rapidly in the trunk main itself, however, simulating the continual mobilisation-accumulation conditions suggests that all layers accumulates simultaneously. This is potentially indicating that accumulation is a process rate dependent rather than the rate of material supply. While a continuous influx of material from upstream can transport to the downstream, accumulation on pipe wall does not necessarily be a supply rate dependent where it would potentially speed up the weak cohesive layer accumulation. The process rate dependent system supports the idea of other discolouration material interacting wall bound properties e.g. biofilms which have also slow growing formations and has varying strength cohesive properties (Abe et al., 2012). This is significant for operational management where irrespective of intervention conditions, e.g. invasive cleaning or new pipe, material potentially regenerate following cleaning at the same speed, and hence the discolouration risk remains same after a while. Therefore regarding alleviating discolouration risk, all cleaning strategies are similarly effective with the primary difference in removing the amount of wall-bound particles for different interventions.

The accumulation rate parameter was found lower (faster accumulation) in the unlined CI mains (TM-2 and TM-3) than the partially lined trunk main (TM-1). While the accumulation rate is slightly higher in partially lined main, output results can be limited to modelling uncertainty range and hence cannot be confirmed from this study alone. However, previous research showed that corrosion contributes to discolouration risk (Cook and Boxall, 2011; Husband and Boxall, 2011, 2010) which is consistent with the accumulation modelling analysis. The longer accumulation rate found for partially lined systems indicates a major benefit may be gained by replacing or lining the unlined cast iron mains to minimise discolouration risk from corrosion processes.

The accumulation rate parameter has been investigated and indicated temperature as a variable. This supports the assumption of material accumulation being a biologically mediated process as higher water temperature is associated with increased microbiological and therefore biofilm activity (Husband et al., 2016) and hence more material accumulating during warmer periods (Blokker and Schaap, 2015b). Higher material accumulation in the warmer season could also be linked to the higher treated water organic and inorganic metal concentrations loadings as shown in Figure 37. Higher temperatures also increase reaction rates and accelerate disinfection decay rates (Ramos et al., 2009; Vasconcelos et al., 1997) which could impact biofilm generation. Research suggests that biofilms may act like massive surface area perforated matrix that captures moving inorganic discolouration particles (Burns and Stach, 2002; Douterelo et al., 2013). With potentially greater biofilm growth more material may trap into the biofilms, elevating the discolouration risk (Blokker and Schaap, 2015b; Ginige et al., 2011; Sharpe, 2012). This process is reflected in the calibrated β_r values. The temperature effect is critical for water utilities, especially with growing concerns about long-term impacts of climate change on water quality. In Netherlands, water temperature is regulated at a maximum 25°C (Agudelo-Vera et al., 2017) to reduce potential water quality failures that may be associated with temperature and biological stability. The model could therefore benefit by having an integrated time variant sub- accumulation model encapsulating water temperature, e.g. Blokker and Pieterse-Quirijns (2013). Adding the sub model, e.g. temperature or biofilm regrowth model, the time-variant β_r would increase modelling complexity and computational time. Also, collecting temperature data from distribution system is not a common practice and hence not practicable to test temperature functionality over discolouration risk. The current model simulation performance is satisfactory and simplified time-invariant model has been demonstrated to produce accurate long-term turbidity simulations.

7.7.3 Operational implications and future works

A primary application of the validated VCD model could be to design flow conditioning interventions to minimise future discolouration risk. In the UK the regulatory turbidity at consumers' taps is 4.0 NTU. With the VCD model accuracy range identified in this work as peak turbidity ±0.25 NTU, this suggests it is a suitable tool to plan against potential turbidity failures, especially when output values can be constrained, e.g. to 1.0 NTU. Prior to use for scenario planning, empirical calibration is currently essential to develop confidence in model output. The VCD model calibration requires hydraulic and long-term data, and this work shows it needs hydraulic event induced turbidity response as well for good calibration. While a single hydraulic event, e.g. flow conditioning, can be used to calibrate mobilisation parameters (α and β_e), however, at least two hydraulic events where turbidity responses should be above mean values, with a defined inter duration between events, are needed for accumulation rate (β_r) parameter calibration. Since the material is structured in varying strength layers, a higher imposed event can mobilise more layers of material than a smaller event and hence provide more accurate model calibration and confidence over simulation. The flow conditioning strategy provides the user with a flexibility and design procedure by which to impose a constraint of material release by managing imposed hydraulic conditions.

The continuous and endemic material accumulation on pipe walls confirmed by this work creates a challenge for the water industry to design network maintenance cycles. The knowledge of site-specific accumulation rates can therefore be an initial move towards proactive discolouration management as this represents how quickly discolouration risk returns on the pipe wall. With accurate β_r determination from the VCD model, whole life costing (WLC) models for designing optimal cleaning intervention cycles can be developed. Careful and further investigation is required of VCD model calibration for the variety and range of networks to understand the significance of parameter variance to pipe material and the subsequent water quality impact such that it can inform decisions on operation expenditure.

7.8 Conclusions

This paper demonstrates the operational long-term system validation of the proposed VCD (Variable Condition Discolouration) model. This is the first known model to simulate material mobilisation and accumulation processes continuously and accumulating material at all strength simultaneously. The key findings are:

- The VCD model can track long-term material mobilisation and accumulation occurring in large diameter pipe systems in response to hydraulic behaviour. It is shown capable of simulating the downstream turbidity response with an average peak turbidity accuracy of ±0.25 NTU using three empirical parameters that are constant for the single run simulation period.

- The accurate turbidity simulation result validates the concept of material mobilisation-accumulation processes occurring continuously, and accumulation occurring at varying shear strengths simultaneously on the pipe wall.

- The empirically calibrated accumulation rate showed consistency for similar network characteristics and source water quality despite differences in imposed shear stress conditions and accumulation periods. The similar accumulation rate under varying hydraulic conditions suggests discolouration risk could return to similar conditions irrespective of cleaning intervention after a while and accumulation is a potential function of process dependent conditions rather than material supply rate dependent processes.

- The VCD model's ability to accurately simulate long-term discolouration behaviour using continuous accumulation and mobilisation functionality facilitates future hydraulic based discolouration scenarios and the development of pro-active network maintenance strategies. Hence the potential significance of continuous tracking ability of VCD model lets user's design cost-effective cleaning interventions using discolouration risk as a criterion to better inform operation strategies.

8. Strategic Planning to Manage Transmission Main Long-term Discolouration Risk

Declaration

The chapter eight is in a format that can be further developed and then be suitable for submission as a journal paper. The contribution of the main author and co-authors are following:

1. **Iftekhar Zaman Sunny** is the PhD candidate and 1st author and major contributor to this published chapter. As a part of his PhD research, he has formulated the aims, developed the methodology, monitored and analysed necessary data and outlined conclusions for this publishable paper. Primarily he has designed and written the chapter having inputs from the co-authors as stated in point 2.

2. **Prof. Joby Boxall and Dr. Stewart Husband** are the primary academic co-authors of these chapters. They have supervised the PhD research project and provided critical input into the research methodology. They have helped to define and refine the aims, overall structure of the thesis, interpretation of results and formulation of discussion points. They also have provided necessary guidance on the chapter content and structure including grammar corrections and correcting sentence structure in order to clarify the sentence meaning.

Iftekhar Zaman Sunny 1st author	Dr. Stewart Husband 2nd author	Prof. Joby Boxall Last author

8.1 Abstract

Managing discolouration risk with a single applied intervention is not considered cost-effective due to continual and endemic material accumulation on pipe walls. This paper presents a novel methodology for designing periodic hydraulic based maintenance interventions, termed "flow conditioning" and investigates the trade-off between operational expenditure (OPEX) and hydraulic resilience. The proposed methodology uses the validated Variable Condition Discolouration model to track the simultaneous mobilisation and accumulation of pipe bound discolouration material for OPEX determination, the first time discolouration behaviour has been used as a sole decision criteria. The experimental design uses idealised trunk main conditions and successfully develops a trade-off curve between imposed system shear stress and discolouration risk-return frequency for a given target hydraulic resilience. Sensitivity analysis of pipe length, diameter and material accumulation rates are all shown to be significant on imposed intervention magnitude and maintenance frequencies. The results are then extended to map the Pareto front between intervention costs and hydraulic resilience, revealing an exponential relationship. This provides operators a unique opportunity to select between levels of resilience considering budget constraints.

Keywords: Discolouration risk, shear stress, hydraulic resilience, cost

8.2 Introduction

It is essential for water suppliers to have a comprehensive network risk assessment for safeguarding water quality and assets to ensure any changes in operation also deliver benefits to the consumers. The supplied water must be safe, aesthetically acceptable and reliable, where the set price should not prevent consumer to use water for fundamental domestic needs with sufficient quantity and quality ,e.g. as agreed in the Bonn water charter (IWA, 2004). However, following treatment, water quality can deteriorate during transit due to various physicochemical, and microbiological processes that create challenges to the water industry to manage the desired service level within regulatory limits. In addition, particles remaining within the bulk water at low concentrations (even after modern water treatment facilities) continuously accumulate on pipe walls along with solutes and microbiological precipitations persistently generating discolouration risk. Accumulated material can be mobilised leading to discolouration and associated water quality issues when hydraulically disturbed, such as following valve operations, rezoning or bursts. Hence a hydraulically resilient network is desirable for the water industry to minimise discolouration risk which can guard against varying hydraulic demands. The necessity of providing the hydraulic resilient network with reduced expenditure is vital for water companies so that it does not impact the consumers by hefty charges and the operator can be commercially viable.

Discolouration as a visible water quality issue is a well-reported risk and causes the highest number of customer contacts worldwide. These hydraulic induced discolouration events are significant for large diameter transmission (trunk) mains due to critical layout position and typically serving high numbers of downstream consumers. Failure to manage these critical assets adequately can damage water utility reputation and consumer confidence with increased financial penalties/incentive being applied by regulators depending on their annual performance (DWI, 2016).

To manage accumulated materials and ensure the network is hydraulically resilient, water utilities regularly exercise various types of network invasive cleaning strategies, e.g., ice pigging, air scouring, swabbing (Friedman et al., 2012). However, these known strategies are expensive, and mains are required to be taken out of service which can disrupt customer service. Several studies reported that material returns to the pipe wall following interventions (Blokker and Schaap, 2015a; Husband et al., 2010) indicating a constant regenerating discolouration risk. Therefore, one-off intervention may not be a solution for managing long-term discolouration risk, and this understanding will likely impact operational expenditure (OPEX).

Since most interventions are expensive and disruptive for the customer, balancing the cleaning intervention expenditure with water quality performance and customer disruption is central to the intervention selection process. The selection of intervention should consider how a network can be hydraulically resilient over its life span period and how financial cost of the intervention can be balanced based on the selected network resilience. Developing an in-service and long-term cost-effective cleaning model would, therefore, be a critical first step with respect to discolouration risk management considering budget constraints.

8.3 Background

8.3.1 Rehabilitation intervention and discolouration Risk

In the UK, selection of drinking water pipe rehabilitation techniques is primarily driven by the short-term benefits and cost (Marlow et al., 2015). However, for cost optimisation, it is sensible to account for all relevant costs and benefits throughout the distribution main service life. Pre 1970, infrastructure investment decisions relied heavily on capital cost alone (Boussabaine and Kirkham, 2008). Later, whole life costing (WLC) concepts were developed based on the idea that OPEX for any asset maintenance could be higher than its capital expenditure (CAPEX). Several researchers demonstrated WLC approach for water distribution networks to minimise total expenditure (TOTEX) that includes both CAPEX and OPEX for a required level of service by maximising desired performance (Conroy and Hughes, 1997; Engelhardt et al., 2002; Skipworth et al., 2002; Jayaram and Srinivasan, 2008). For water quality improvement, water utilities typically exercise different types of rehabilitation techniques, e.g. pipe replacement, relining of old cast iron (CI) main, invasive cleaning. Rehabilitation decision and prioritisation models to address structural performance and water loss have been developed using diverse performance criteria, e.g. burst rate and asset age (Engelhardt et al., 2003), integrating GIS, hydraulic data and breakage models (Tabesh and Saber, 2012), use of cost function based on pipe replacement, rehabilitation, repairs and pumping cost (Kim and Mays, 1994), and pipe failure and replacement cost using Bayesian parameter estimation (Scholten et al., 2014). The above-mentioned models were mostly focussed on structural performance and water quantity; none of the models considers water quality performance as a criterion.

While replacing pipe or relining unlined CI mains can reduce discolouration risk (Engelhardt et al., 2000; Husband and Boxall, 2011), previous studies have not assessed their performance based on discolouration risk. It is also noted that bursts have a cleaning effect on pipe walls as they create a hydraulic disturbance and mobilise accumulated discolouration material. Cook (2007) observed after companywide long-term bursts assessment that there was a reduction in discolouration based customer contacts in the summer season following a higher number of recorded bursts during the winter period. However, forecasting bursts events and associated effects on discolouration risk is relatively complex to evaluate and not yet well understood and the corresponding model should encapsulate discolouration processes as well.

Primarily, the decision models compared CAPEX investment, e.g. installing new pipe, with ongoing OPEX, e.g. pipe repair, to hence minimise overall TOTEX. Skipworth et al. (2002) proposed a WLC methodology considering periodic flushing of distribution pipes to reduce accumulated material and relining of unlined cast iron mains (thereby removing a source of discolouration material from corrosion) to reduce the required flushing frequency. However, apart from the conceptual proposals, no further study on this WLC methodology has been reported. Most of these models have primarily been proposed or developed for small diameter pipes. However, large diameter pipes have relatively lower shear stress conditions and mixing of material due to the higher ratio of water volume to surface area can have a different effect on discolouration behaviour. Thus methodologies to manage trunk main discolouration risk or investigate associated TOTEX for trunk main interventions are as yet unknown.

8.3.2 Material accumulation rates and maintenance interval

While one-off invasive interventions or rehabilitation techniques, e.g. relining, can reduce discolouration risk over a short period within the assets lifetime, material accumulation following intervention raises questions about the sustainability of these for an extended period and the associated OPEX benefits. Therefore in order to assess the cleaning intervention OPEX and reducing overall TOTEX, knowledge of the rate at which material returns is a key criteria defining maintenance intervals (Boxall et al., 2003a).

Various research has showed that material responsible for discolouration accumulates continuously and ubiquitously in distribution systems (Boxall et al., 2001; Blokker et al., 2011; Cook and Boxall, 2011; Husband and Boxall, 2016). Accumulation process are influenced from a number sources and factors highlighting its endemic nature in water distribution network e.g. bulk water (Vreeburg et al., 2008; Blokker and Schaap, 2015a), pipe material (Husband and Boxall, 2011), hydraulics (Cook and Boxall, 2011; Pothof and Blokker, 2012), temperature (Sharpe, 2012; Blokker and Schaap, 2015b).

Some studies investigated material accumulation return period for distribution pipes of less than 150 mm (6”) reported between 1.5-4.0 years through repeated flushing (Husband and Boxall, 2011) and 1.5 years with resuspension potential method (RPM) trials (Vreeburg et al., 2008). While Husband and Boxall, (2011) estimated based on annual repeat flushing frequency, Vreeburg et al., (2008) extrapolated the return rate from repeated RPM trials information. Richardt et al., (2009) developed a flushing decision model based on pipe specific turbidity potential for estimating possible flushing return intervals and found between 0.5-8.0 years. Assessing accumulation return period using flushing or RPM methods is particularly complex for trunk mains due to their critical nature and the flows required. Therefore little information is currently available about material accumulation return interval or rates for large diameter pipe systems.

8.3.3 Discolouration processes and behaviour simulation

Discolouration processes primarily consist of material mobilisation and accumulation that can occur simultaneously on pipe walls (Husband and Boxall, 2011). Field evidence showed that accumulated material can be mobilised due to an increase in velocity or shear stress above normal prevailing hydraulic conditions (Boxall et al., 2001). Flushing data has evidenced that material is mobilised at consecutive shear stress step increases, analogous to material arranged in cohesive shear strength layers (Boxall et al., 2003b; Husband and Boxall, 2011).

While observed material mobilisation can be described as occurring from weak to strong layers, repeated flushing results demonstrate accumulation occurring across all shear strength layers simultaneously (Husband and Boxall, 2011; Husband et al., 2010). This accumulation across the shear strength range has been verified in full-scale temperature controlled laboratory conditions (Sharpe, 2012). The accumulation process indicate that how discolouration risk changes accorss varying strength cohesive layers. Therefore it must be captured or simulated to estimate the accumulation rates and using this information, cost of intervention can be designed effectively. Repeated flushing has also demonstrated that material accumulating linearly over time irrespective of seasonal variations (Cook and Boxall, 2011).

Based on the operational evidence of discolouration processes, Furnass et al., 2014 developed a Variable Condition Discolouration (VCD) model that simulates long-term discolouration behaviour by tracking both material mobilisation and accumulation processes simultaneously. The model tracks the material present across a number of shear strength bands with accumulation defined as occurring at all shear strengths continuously up to a hydraulically limiting maximum. The mobilisation process assumes cohesive layers remain in equilibrium conditions with current prevailing hydraulic (τ_i) and only mobilises during excess applied shear stress (τ_a-τ_i) conditions when $\tau_a>\tau_i$. Material accumulation occurs when applied shear is lower than the prevailing hydraulics ($\tau_i>\tau_a$). The mobilisation and accumulation processes are represented by β_e (mobilisation rate, $N^{-1}m^{-2}s^{-1}$) and β_r (accumulation rate, s^{-1}). A third parameter α (material release coefficient, $NTUms^{-1}$) is a linear scaling factor. To reduce modelling complexity, the three model parameters are currently designed as scalar and invariant with time and shear strength. The model tracks the relative amount of material [φ (τ,t)] within the range of 0 to 1.0 where 0 means no material on the pipe wall and 1.0 means maximum amount for a given layer strength (Furnass et al., 2014). The model assumes material binds uniformly and ubiquitously on the pipe wall, recreating field evidenced flushing data (Boxall and Saul, 2005). Turbidity is treated as a concentration in the VCD model taking account of its linear correlation to total suspended solids (Boxall et al., 2001; Vreeburg, 2007).

The model functionality was initially tested using synthetic data and calibrated for both small diameter and trunk main measured data (Furnass et al., 2014). The model has since successfully simulated long-term measured data, validating the concepts in multiple trunk mains (Chapter 7, Husband and Boxall, 2017). Validation of this model highlights the ability to simulate long-term discolouration behaviour, however, design methodologies utilising this novel understanding, are yet to be developed.

8.3.4 Non-invasive hydraulic based discolouration risk management

A cohesive transport model was proposed by Boxall et al., (2001) that discolouration layer binds on pipe wall ubiquitously and has varying cohesive strength properties. Based on this theory an in-service trunk main cleaning strategy termed "flow conditioning" was developed by the University of Sheffield collaborating with several UK water companies (Husband and Boxall, 2015). The flow conditioning can be described as "controlled in-service flushing" based on knowledge of historical hydraulic and network properties and managing the impact of increasing shear stress. On contrary typical flushing operates by increasing pre-defined shear stress or velocity until the base turbidity level reduced to target values.

Flow conditioning strategies have been designed to mobilise material into the bulk water yet keep the response usually below a target value, such as the Prescribed Concentration Value (PCV) limit at the customer's taps in the UK of 4.0 NTU. This is achieved by imposing an excess system shear stress (τ_a-τ_i) until all material with strength below the imposed shear stress is mobilised. The remaining material is then considered "conditioned" to this imposed excess shear stress and would require further increases in shear stress to be mobilised. The ability to use multiple flow conditioning steps and manage the response at each stage allows target flows, or the desired system resilience, to be achieved. As a result, this strategy can be used to prevent discolouration risk from both planned and unplanned events, e.g. rezoning and bursts. However, due to the continuous material accumulation (Cook and Boxall, 2011), periodic flow conditioning is then required to preserve the benefits. This method has been successfully implemented in several trunk main systems (Cook et al., 2015; Husband and Boxall, 2015) and its long-term water quality benefits have been demonstrated as part of water treatment works (WTW) outlet to downstream network approach (chapter 4 and chapter 5).

To determine the flow conditioning OPEX, a trade-off between the imposed event magnitude and the return frequency for a defined system resilience to protect against discolouration risk is sought. In this case, system or hydraulic resilience is a discolouration risk index. While the VCD model encapsulates the cohesive transport theory and has successfully simulated flow conditioning for multiple trunk main systems (Husband and Boxall, 2017, Chapter 7), no study has used the VCD model to determine the trade-off between the imposed shear stress magnitude and the risk-return frequency. Therefore, long-term costs of flow conditioning and how to design maintenance schedules cost-effectively remains unknown.

8.4 Aim

The overall aim of the paper is to demonstrate how to design flow conditioning cycles to manage discolouration risk by trading cost against hydraulic resilience. The aim is spilt into further two objectives as: a) determine the cost of flow conditioning intervention for a specific period; b) determine the trade-off between intervention costs against hydraulic resilience using VCD model functionality.

8.5 Methods and materials

8.5.1 Methodology

A methodology was developed for modelling periodic flow conditioning interventions considering cost compared to hydraulic resilience. The first stage of the design process required simulating flow conditioning shear stress and then predetermined event conditions to ensure that mobilisation of the remaining discolouration material from the pipe wall never exceeded a discolouration threshold within the given period due to a target hydraulic resilience event. The remaining material that would be mobilised by the target hydraulic resilience event resulting in peak turbidity at the downstream of pipe is referred to as 'critical material' and unless stated otherwise a threshold 4.0 NTU to match UK PCV was used. It is also to be noted that following flow conditioning, material accumulates again prior to hydraulic resilience event, meaning that this contributes to the amount of critical material as well.

To track critical amount and design flow conditioning magnitude and return period, the validated "Variable Condition Discolouration" (VCD) model can be used to simulate material mobilisation and accumulation simultaneously across the range of shear strength layers. In order to investigate the discolouration risk-return period for varying imposed shear stress interventions, the model was tested initially against a fixed hydraulic resilience. As different magnitude flow conditioning interventions have different risk-return periods, cost determinations were different for each imposed intervention. The minimum cost to ensure resilience against fixed hydraulic event was assessed from a trade-off curve between intervention magnitude and periodicity. Once the method for identifying the minimum costs for periodicity and magnitude of flow conditioning for a given resilience was assessed, different resilience levels informing a true trade off curve or Pareto front for cost against resilience were explored.

Most trunk mains can be split into two hydraulic groups, those linking network components and hence with utility controlled flows, e.g. between treatment and reservoir, or demand-driven mains supplying customers directly. In the former, networks typically have a level of risk buffer, e.g. higher storage during repair, so that risk can be delayed or even mitigated with appropriate measures. With the correct infrastructure, it is feasible to automate repeat flow conditioning trials after an initial trial. In these circumstances, long-term flow conditioning strategies can be effectively cost-free and become part of business as usual protocols. However, for demand-driven networks managing hydraulics is more complex as there is no certainty of peak demand and, hence, without any risk buffer or break present prior to water being delivered to the customer any risk that propagates within the network, e.g. discolouration risk, can directly impact on the end users. Due to its demand driven nature, mains automation of flow conditioning trials is not possible in this case and manual on-site intervention is required to control flow and associated turbidity responses. To demonstrate how flow conditioning long-term options can be modelled, idealised daily flow patterns and hydraulic properties, e.g. length, diameter, roughness based on real network, were chosen. The daily flow patterns were chosen based on ease of interpretation with no seasonal or daily variation. Since interventions were to be manually controlled by increasing shear stress on-site and water was to be discharged in a manner similar to a flushing operation, data on water usage and resource unit cost to undertake such operations, e.g. equiment setup, travel to the site, were considered in the cost framework.

A range of sensitivity analyses were undertaken to evaluate the effect of parameters on the applied shear stress and its risk-return frequency output for a given resilience. Regarding parameters, preference was given to those which have a significant influence on flow conditioning operational aspects, e.g. cost and strategic modelling, and those typically invariant with time, e.g. hydraulic structure.

8.5.2 Framework for flow conditioning long-term modelling to guard against discolouration risk

The relationship between the imposed shear stress interventions and discolouration risk-return intervals was determined by tracking the amount of material on the pipe wall that could be mobilised by a given target hydraulic event. Figure 50 presents how material layers are structured in the VCD model during normal operation with no intervention and the effect of increased hydraulics. Using VCD model concepts, cohesive layers are conditioned by the daily peak shear stress (τ_D) during normal operational conditions, point 1 Figure 50. If an event (τ_R) occurs at any period (point 2 Figure 50), the amount of material mobilised (marked in red) can cause a discolouration event potentially leading to a PCV failure. Following mobilisation, the remaining material potentially has a shear strength equal or higher than τ_R event. The target to designing flow conditioning repeat interventions is therefore such that the remaining available material to be mobilised due to τ_R at any time never exceeds a discolouration threshold, in this case a peak of 4.0 NTU at the downstream end of the pipe, at any given period.

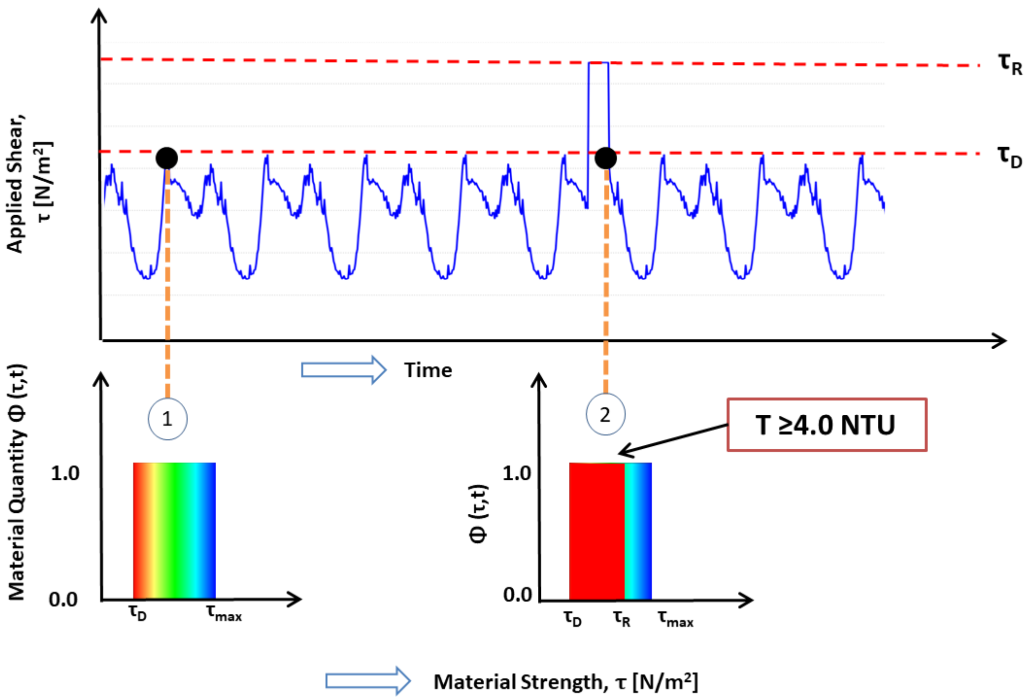


Figure 50: Varying strength material conditions at given time and the effect of the hydraulic event on the material amount – normal conditions without any interventions. τ_D [N/m^2] is maximum daily peak shear stress, material accumulation below this strength is in a continual daily cycle of accumulation and mobilisation and hence is effectively zero, τ_R [N/m^2] is hydraulic event shear stress, and τ_{max} [N/m^2] is the hydraulic network specific maximum material shear strength – for these simulations this was kept high enough to effectively be infinite so did not affect simulations. The rainbow colour pallet shows varying cohesive strength material present on pipe wall during normal operation limited between φ = [0,1.0] where material strength increasing from left (red) to right (blue), T represents max turbidity [NTU] at the downstream end due to the τ_R event and the red box shows amount of mobilised material due to the τ_R event causing discolouration risk (≥4.0 NTU).

Figure 51 depicts the cyclic design procedure for flow conditioning interventions to guard against τ_R events at any given design period. If a target conditioning shear stress (τ_c) is implemented as shown at point 2 Figure 51, all material with shear strength below τ_c is mobilised from the pipe wall. Material then accumulates again across all shear strength simultaneously (Husband and Boxall, 2011), shown at point 3. Similar to point 2 and 3, target strength material is mobilised due to the τ_c event at point 4 and point 5. If a hydraulic event (τ_R) occurred at point 6, this would mobilise relatively less material (L-shaped red marked area) due to the pro-active removal by flow conditioning than shown in Figure 50 without any controlled interventions (red marked area). The repeat cycle of flow conditioning interventions has to ensure that the total mobilised material by the event (the amount equivalent to the L shaped red marked area) should remain below the discolouration PCV of 4.0 NTU, i.e. the critical amount. It is essential to maintain the same initial trial magnitude for repeat intervention so that each repeat intervention mobilises a consistent amount of material in every cycle. This will ensure the tracked critical amount is the same and providing an accurate risk-return period for a given configuration

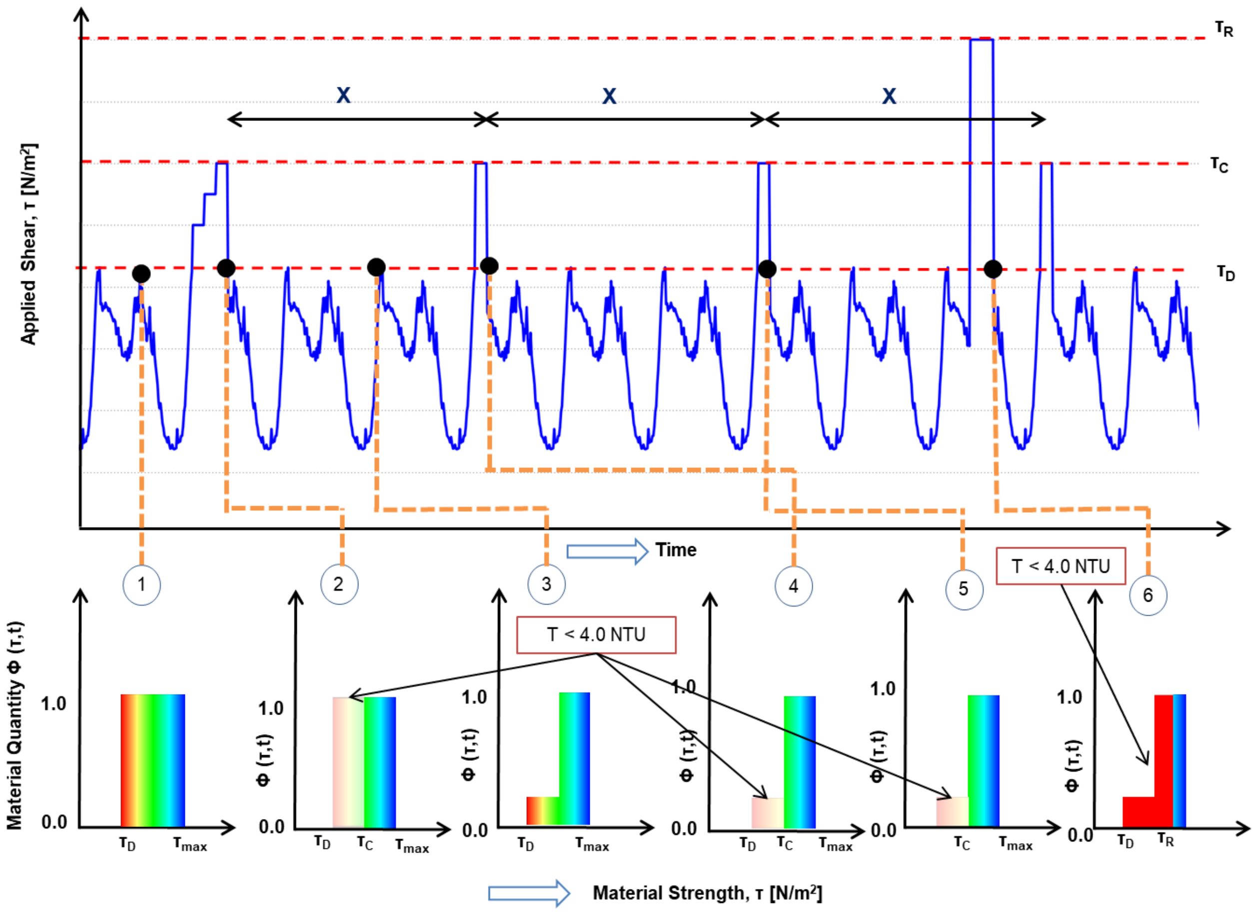


Figure 51: The conceptual basis of material mobilisation and accumulation for discolouration management decision framework. Here τ_c [N/m^2] is representing flow conditioning shear stress magnitude. Transparent layer indicated the material just mobilised at the time due to the τ_c event, and X represents the risk-return frequency of the τ_c event. Red represents the amount of material mobilised by the τ_R event and is the critical material amount which must be less than 4.0 NTU at the downstream end of the trunk main when mobilised to satisfy the resilience criteria

Figure 52 presents the various configurations for designing flow conditioning trials to guard the network against a hydraulic resilient (τ_R) event. The Figure 52 illustrates how target resilience can be achieved by imposing higher magnitude low frequency or lower magnitude higher frequency interventions.

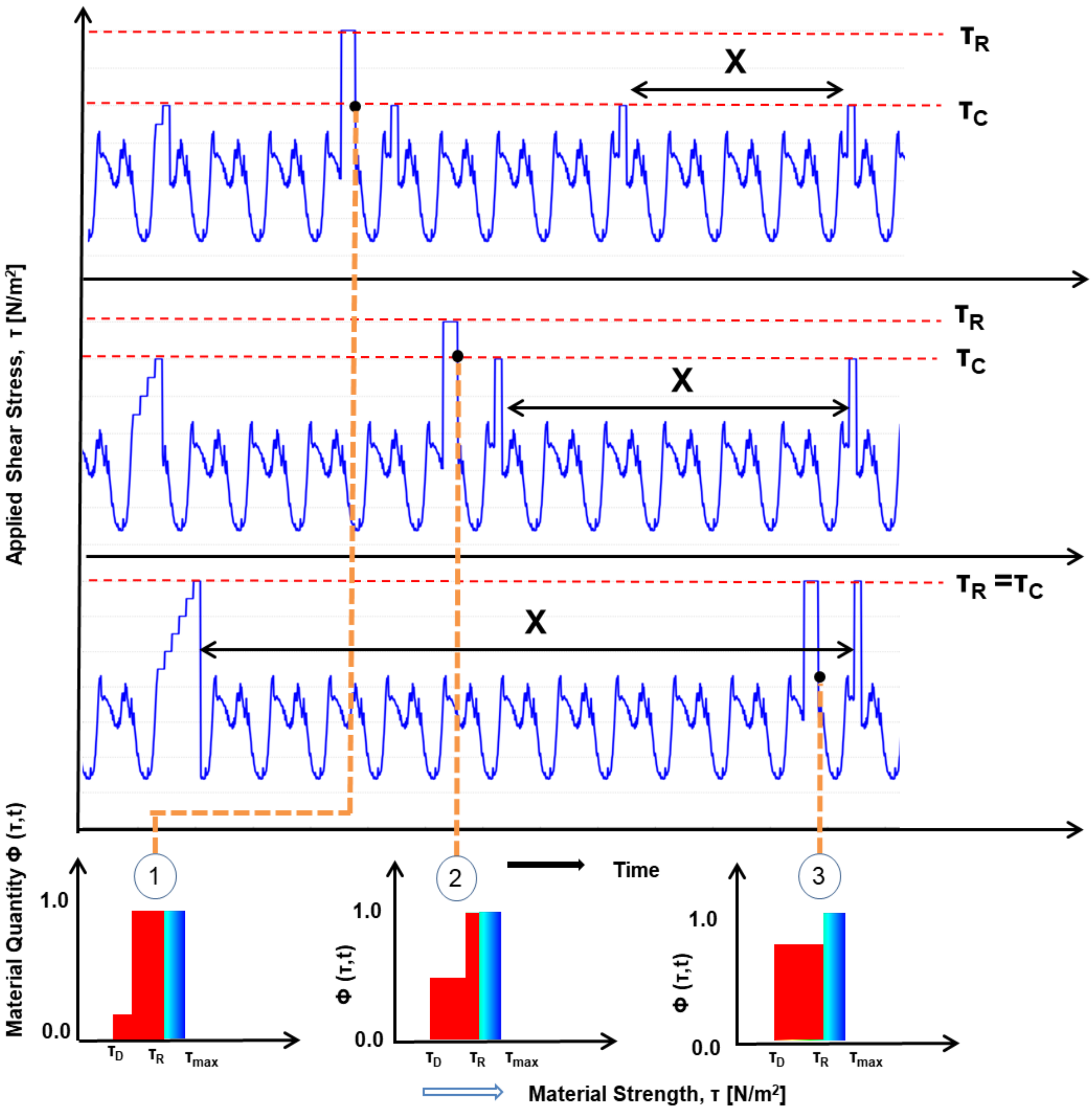


Figure 52: Discolouration risk management by balancing flow conditioning magnitude and return frequency. Three scenarios are presented; top plot lower intervention magnitude with higher return frequency, middle plot medium magnitude and frequency and a bottom plot higher magnitude with lower frequency. All scenarios provide same hydraulic resilience (τ_R) with the critical amount (marked red) limited to target threshold

8.5.3 Case Study: Idealised model conditions

The conceptual basis of discolouration management framework as shown in Figure 51 was tested in the VCD model for idealised trunk main conditions in a demand driven network requiring manual intervention. The model was developed for a single pipe length of 1.0 km with an effective internal diameter (ID) of 228.0 mm (9") and pipe roughness (k_s) 5.0 mm. This was based on a real operation trunk main of interest, but simplified and obfuscated for confidentiality reasons. The model accumulation return period was selected as 1.0 year, taken from previous findings (Husband and Boxall, 2011; Furnass, 2015; Furnass et al., 2014) and representative of the surface water source and cast iron pipe material of the real system. To demonstrate the relationship between imposed shear stress magnitude and risk-return frequency, a 24 hour fixed diurnal flow profile with a maximum peak of 20 l/s (=0.55 N/m^2) was selected. A 24 hour fixed diurnal pattern was chosen for the simplification and ease of representation. In normal operation demand profiles can vary, influencing the amount of material on the pipe wall. For this work, however, this is not critical as model resilience was tested against extreme hydraulic cases.

Even though the upstream end of the pipeline on which these simulations is based is a water treatment work, the incoming mass flux of turbidity would not be zero. In order to account for this effect the simulations were run with a turbidity of 0-0.3 NTU generated using normally distributed random numbers. This was based on a previous study (chapter 7) and normal UK practice that targets WTW outlet turbidity well below the 1.0 NTU regulatory limit (DWI, 2012).

The current layer strength profile is a vital parameter in the VCD simulations (Furnass, 2015; Furnass et al., 2014). In order to ensure this was accurate at the time of interest, an initial period of three months was added starting with a fully developed layers (φ=1.0) and the turbidity results from this period ignored. The results for this simulation period were not included here. The VCD model requires the material layers to be described by a number of discrete bands. Based on previous work this was set to 100, found to be more than sufficient to accurately simulating measured data (chapter 7, Figure 41).

While this study used demand-driven flow patterns assuming the main was supplying water directly to downstream consumers, the intervention turbidity simulated response was constrained to 1.0 NTU to provide a significant safety margin over regulatory 4.0 NTU. Peak turbidity due to shear stress increases occurs at approximately one pipe turnover when the water parcel has gathered potentially the highest amount of material when it reaches downstream point of interests (Furnass, 2015). As a result all planned trials simulated for >1x turnover to allow complete target strength material mobilisation from the pipe wall.

An event of additional 15 l/s to the daily peak (=total 35 l/s peak demand) was used as the initial fixed resilience target, based on an operational requirement of the real system. This is equivalent to shear stress of 1.5 N/m^2. Fixed resilience was selected high enough compared to the peak shear of 0.55 N/m^2 (=20 l/s). Each intervention event (τ_R) duration was implemented >1x pipe turnover as stated previously as an idealised condition.

8.5.4 Pareto front assessment for OPEX against hydraulic resilience

The trade-off curve of cost against hydraulic resilience for a fixed resilience can indicate a minimum cost required to protect against a given resilience, however, it can not encapsulate the required OPEX to maintain varying hydraulic resilience. Knowledge of pre-selected resilience is often unknown for a given network. To determine trade-off curve between interventions OPEX against any level of hydraulic resiliencee, Pareto efficient method was used to generate a set of independent solutions to develop a true Pareto frontier or front where below this curve no best solutions (here, minimum cost) can exist. This method was applied by assessing the minimum cost for imposing interventions for a fixed resilience (=1.5 N/m^2) and the the same costing assessment was conducted for varying resilience to determine the true pareto front of hydraulic resilience and intervention cost. The lowest resilience point at the pareto solutions were identified when below a τ_R event the model does not produce 4.0 NTU, whilst higher resilience is effectively infinite. For this paper, the upper bound of 2.5 N/m^2 (=46 l/s) resilience was selected to evaluate the Pareto front solutions. To map the Pareto set of intervention cost against hydraulic resilience, minimum cost solutions for each resilient event was then used.

8.5.5 Sensitivity study of shear stress and return frequency

Sensitivity tests were carried out by changing the network physical characteristics and model parameters to evaluate the influence on magnitudes of imposed interventions and return frequency output. Network hydraulic properties (length and diameter) and model accumulation rate (β_r) were selected as variables for this study. The length (L) and diameter (D) were chosen as invariant with time. Both L and D influence the volumetric amount and travel time of the discolouration material. Diameter additionally influences imposed network shear stress. The effects of L and D are more readily apparent in the fixed resilience plots and extrapolation to moving the Pareto curves is trivial as they are induced from fixed resilience curve and lifts or suppress the Pareto front. Hence sensitivity tests for L and D focussed on the initial trade-off curve developed with a fixed resilience of τ_R =1.5 N/m^2 and a daily peak shear stress of 0.55 N/m^2. Other hydraulic property, e.g. pipe roughness was not accounted due to its potential variability over time in response to varying hydraulic conditions and hence quantifying results become complex and no significant impact on any trade-off curve.

The effect of accumulation rate (β_r) was tested for both fixed resilience and Pareto front as β_r accounts change in source water quality and can inform operation decision. This β_r value range was chosen from the previous findings of 1.5-4.0 years (Husband and Boxall, 2011; Vreeburg et al., 2008). While improving treated water quality can reduce accumulation rates and hence influence the cost profile, β_r sensitivity tests were undertaken for both shear stress and cost against resilience trade-off. The sensitivity of VCD model parameters defining mobilisation (β_e and α) is not considered or discussed due to the contractual conditions with the sponsoring company of this project.

8.5.6 Costing framework

Flow conditioning cost assessment was split into two parts: a) resource cost to operate the intervention on-site and b) water usage cost.

To quantify the resource cost, two employees have been identified as required on-site for implementation, in accordance with common health and safety practices. The work process includes valve management, equipment setup, data collection and health, safety and risk assessments. It was assumed that each trial would require five hours of operation including field work with minimum one pipe turnover trial duration. Travel cost to the site has not been included as it is more site-specific. The employee unit hourly cost was taken from the UK national minimum wage of £7.5 per hour (www.GOV.uk). Considering employee pension, overhead management cost, various insurances and travel allowance, it was assumed that resource cost would be three times unit rate (2*7.5*3 = £45.0 per hour).

Since this work demonstrating flow conditioning trial in a demand driven network, excess shear stress or water disposal was considered by hydrant discharge similar to flushing operations. It was assumed discharge did not incur to any direct wastewater cost. For the costing framework, discharged bulk water cost was determined as 0.8368 £/m^3 (Scottish Water, 2013) which included internal maintenance, water treatment and pumping cost.

UK water companies' financial regulatory cycle is currently set at five years and hence for this study, a five year design period was selected for cost assessment. To normalise the future cost to its present value, all flow conditioning intervention associated costs were converted to their net present value (NPV) by using a discount rate of 3.5% (HM Treasury, 2003). The NPV cost was calculated by equation 1.

$$NPV = \sum_{n=0}^{n} \frac{C_n}{(1+i)^n} \quad (1)$$

Where, NPV = Net present value (£), C_n = operational cost at year n (£), i = discount rate (%), n = duration of cash flow (year)

It is noted that additional design and management related cost was excluded from this costing calculation as these are more business specific. Equipment costs such as flushing standpipes, turbidity monitoring equipment, vehicles etc., for flow conditioning was also not included as those are part of CAPEX investment or standard water company inventory. The costing framework could be readily expandable and adaptable to include or exclude costs as required.

8.6 Results

8.6.1 Applied shear versus return frequency trade-off curve for given network resilience

Figure 53 presents the relationship between applied shear stress and return frequency to protect against a τ_R (=1.5 N/m^2) event generating downstream turbidity greater than 4.0 NTU. Figure 53 demonstrates that the higher the imposed shear, the longer the return period and vice-versa. This relationship followed up to a certain point (1.2 N/m^2) from where the return period remains constant (105 days). It is evident from Figure 53 that after 1.2 N/m^2 simulation responses was dominated by the lower part of the 'L' shape and conversely below 0.9 the output was dominated by the upper part of the 'L' shape. However, between these upper and lower band, a trade-off region exists that was influenced by complex material conditions. The result demonstrates that it is not necessary to increase imposed shear stress up to the τ_R event magnitude and highlights discolouration risk can be managed with lower shear stress interventions. For this scenario, the result indicates a daily return period with a 0.925 N/m^2 imposed shear stress intervention, or 80 days with a 1.0 N/m^2 imposed shear stress intervention. Below 0.925 N/m^2 the network cannot protect against the defined discolouration risk (≥4.0 NTU) with the current network configuration. Above τ_R (=1.5 N/m^2) event, return period was found constant. It is important to note that in all cases, network resilience was designed to protect against the same τ_R event meaning all interventions (0.925-1.75 N/m^2) provided the same discolouration risk protection, but require different amounts of water, different durations on site and frequency of visits and hence have different costs associated.

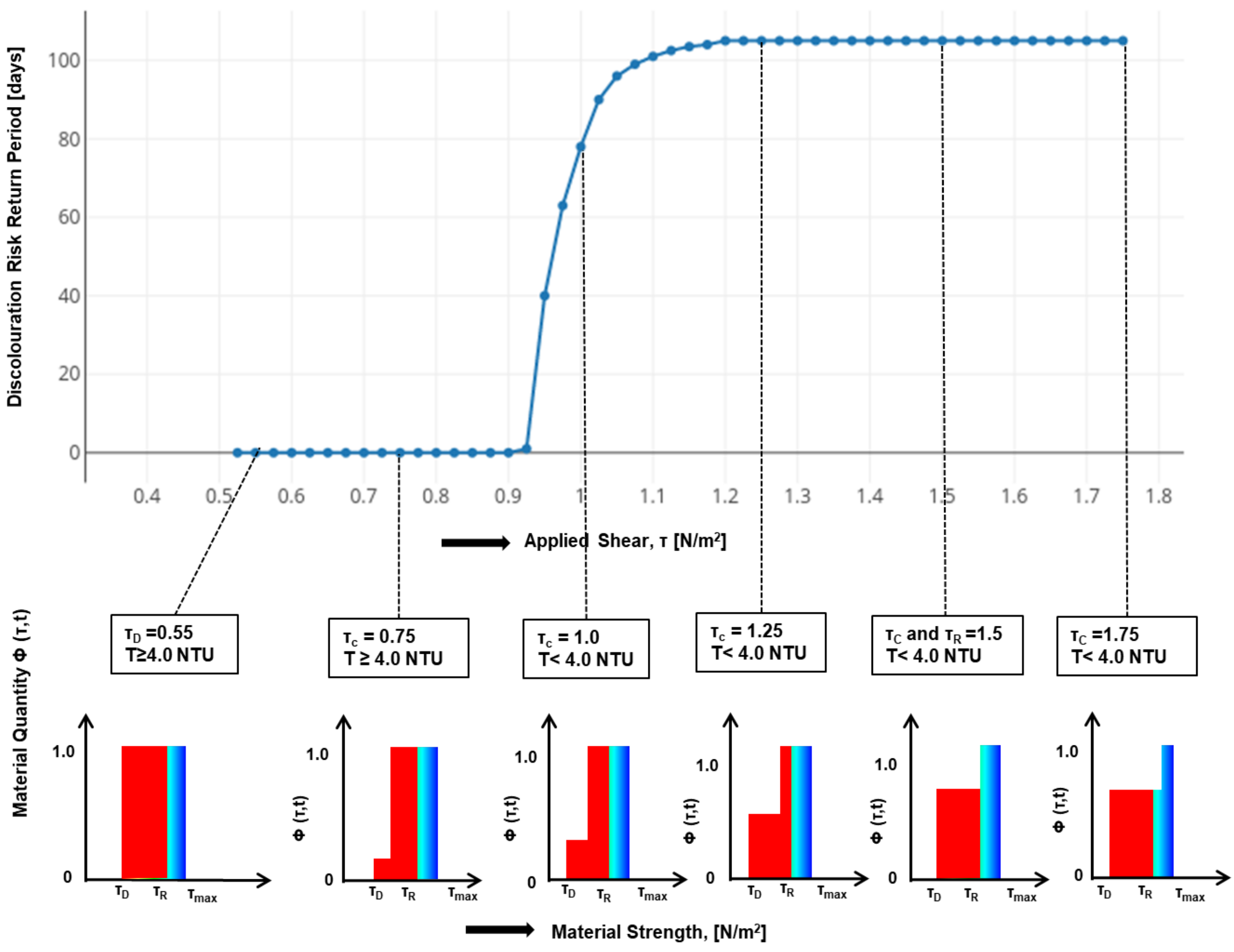


Figure 53: Trade-off curve of applied shear stress magnitude and risk-return period and material conditions following the fixed hydraulic resilience (τ_R) event (=1.5 N/m^2). The top plot shows varying

imposed flow conditioning events to protect against τ_R event and risk-return period in days for an idealised model. Bottom plots represent material conditions in the VCD model, showing the amount of material (in red) that would be mobilised if the target resilience event occurred just prior to each repeat intervention – the worst case time.

8.6.2 Cost assessment for a fixed resilience

Figure 54 presents the flow conditioning intervention cost projected in a five-year financial period determined from the trade-off curve (Figure 53) for a network resilience of τ_R=1.5 N/m^2. The lowest cost for the given resilience identified from Figure 54 was a flow conditioning target of 1.125 N/m^2 with return period of 102 days. Results depict that the lower the imposed shear stress, the higher the cost. However, this relationship holds valid for below the minimum cost point. Above 1.125 N/m^2, steps are evident in the cost profile. These are due to the need for visits to span over more than one site visit and the associated costs. The cost for a one day return period and flow conditioning target flow of 0.925 N/m^2 is £452070, not shown in Figure 54 due to y-axis scaling to focus on operationally pragmatic intervention schedules.

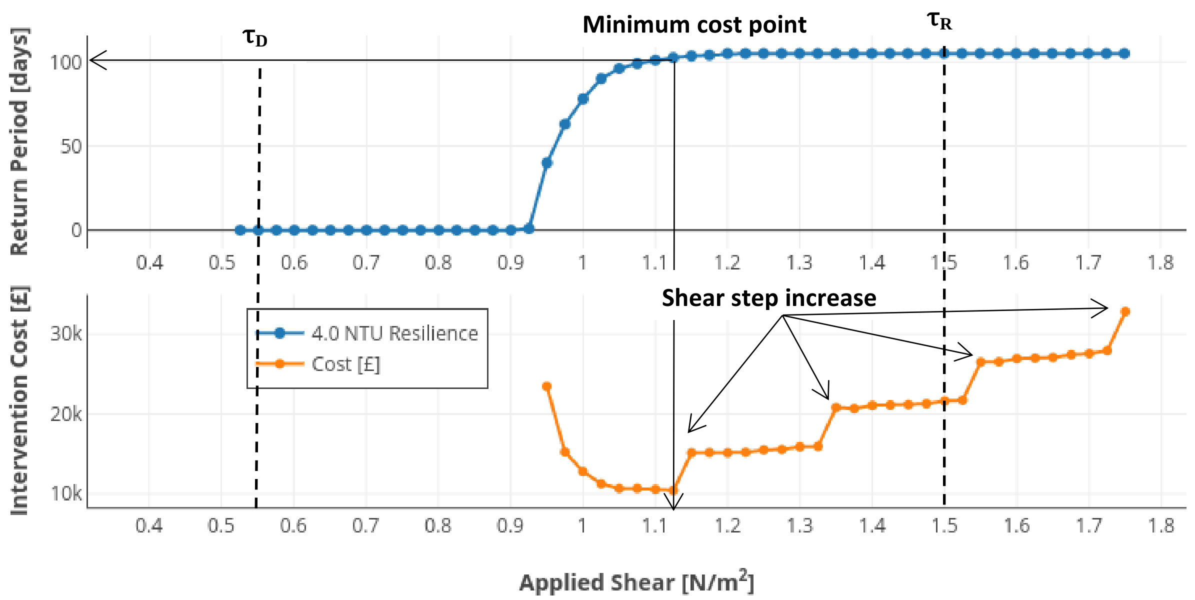


Figure 54: Intervention cost assessment based on imposed shear stress magnitude and risk-return period for a fixed hydraulic resilience (τ_R = 1.5 N/m^2)

Figure 55 presents the cost breakdown of flow conditioning events that had at least a one day return period. The cost analysis in Figure 55 demonstrates the proportion of initial cost compared to the repeat intervention costs for a five-year financial period. The plot demonstrates repeated trial resources dominated total cost where approximate ~80% of the total cost incurs from resource usage and the rest of the cost (~20%) was from water usage. As expected due to the number of repeat interventions within the five-year interval, repeated trial water usage cost was also higher compared to the initial trial water usage. At one day return with an imposed shear of 0.925 N/m^2, repeated trial costs accounted for almost the total cost which was anticipated due to the 365 annual repeats.

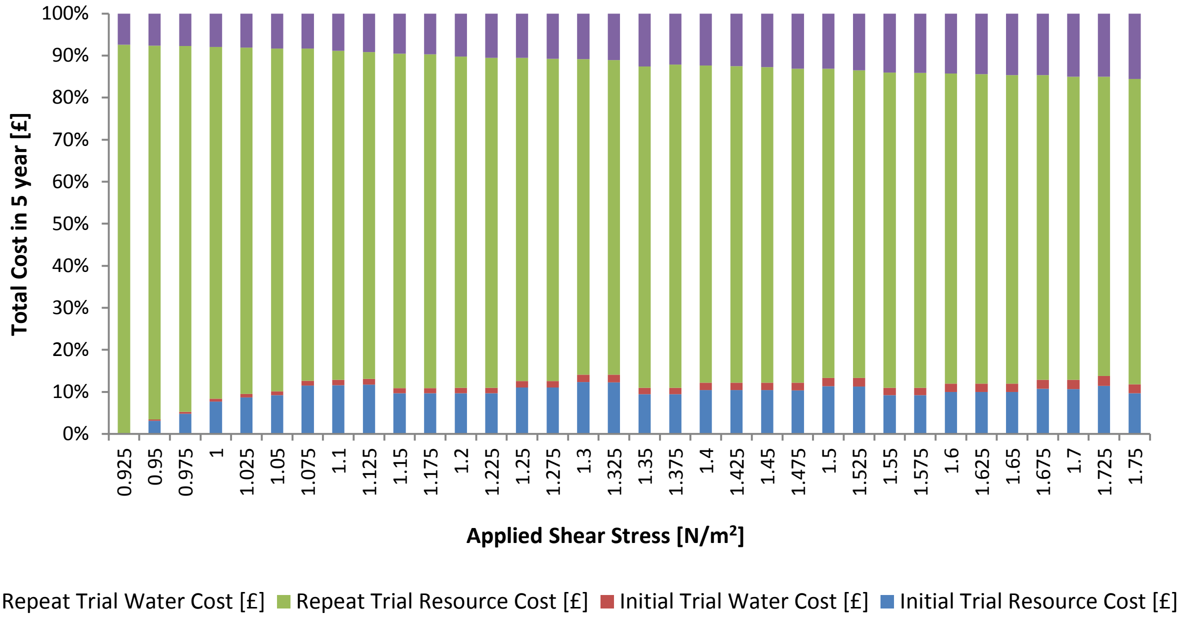


Figure 55: Cost breakdown of imposed intervention to protect against τ_R (=1.5 N/m^2) event

8.6.3 Cost assessment for varying resilience: Pareto front assessment

Using the same method to determine the costs for a single defined resilience, the minimum cost for different resilience targets was determined as shown in Figure 56. The Pareto front or set solutions shows that intervention costs over five years increased exponentially with increasing τ_R conditions. An exponential function explained the cost correlated to the resilient event with R^2 = 0.98. Below 1.25 N/m^2, τ_R event did not create a 4.0 NTU discolouration risk with the current network configuration, and hence this was considered the minimum point. While picking pre-set resilience event as a prior is often challenging, this exponential relation allows determining the optimal set of OPEX for any resilience. Hence this model can be utilised as a decision support model. Using this plot an operator can select the required resilience target considering budget constraints. For example with a 25% cost compared to maximum expenditure (up to £82000 to protect the network to 2.5 N/m^2), the network can be resilient up to 1.75 N/m^2.

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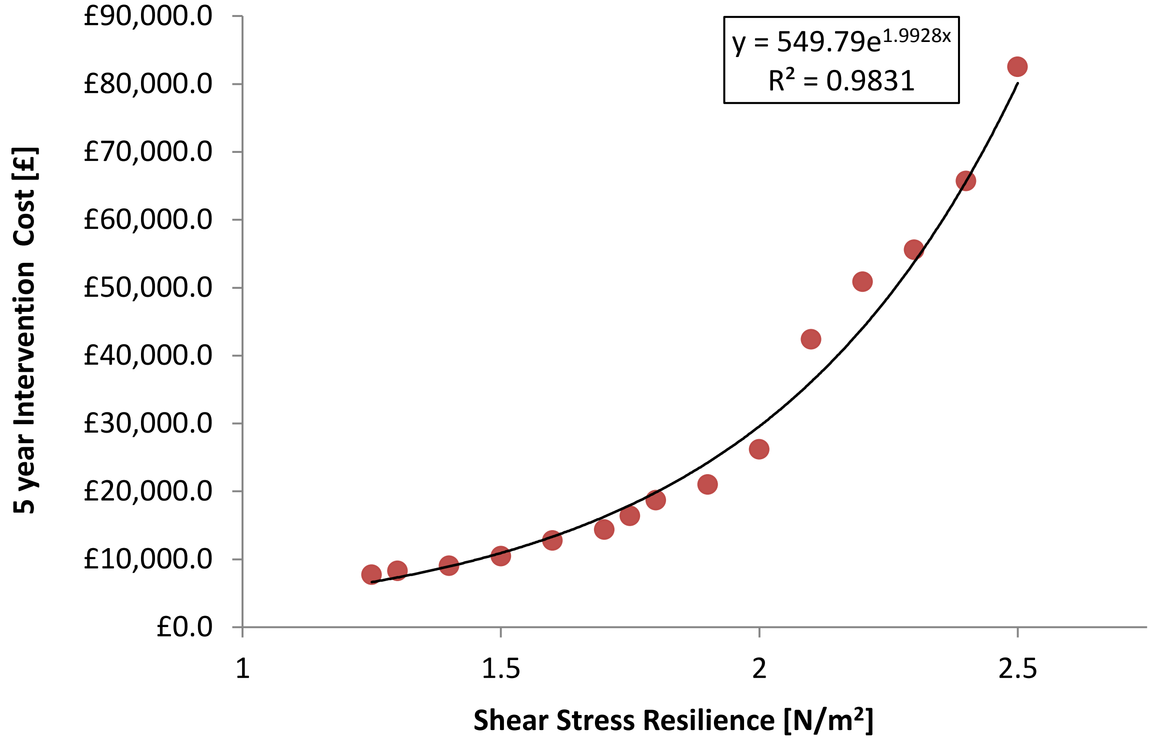

Figure 56: Pareto front curve for minimum cost of flow conditioning intervention strategy to achieve a range of resilience levels.

8.6.4 Sensitivity analysis of trade-off curve for given resilience

8.6.4.1 Length and diameter

Figure 57 is the sensitivity analysis showing how different pipe lengths impact applied shear stress and intervention return frequency trade-off. The plot shows the shorter the length, the longer the return period. As can be seen from Figure 57, the trade-off curve was sensitive to lower imposed shear stress compared to the higher events for length variations. However, after about two km the maximum return period converged. Pipe length as a variable showed that for longer pipes with relatively higher imposed shear stress, return periods were relatively consistent (Figure 57). Change in return period observed as pipes get longer is initially due to increasing amounts of material accumulating with the greater surface area available as the model assumes material accumulates on pipe walls uniformly. Typically peak turbidity due to the imposed interventions occurs at one pipe turnover. However once the peak turbidity occurs for a specific configuration when all material is mobilsed into the bulk flow, this acts as a block of volumetric material being transported and peak turbidity does not increase anymore. Since τ_R event mobilises the same amount of material per unit area irrespective of length, peak turbidity in shorter pipes is therefore associated with the pipe turnover volume. However when a certain pipe length is reached, all accumulated material of specific strength depending on imposed event can be mobilised before the time taken for a pipe turnover. When this occurs, at around two km in the configuration used here, turbidity values plateau at a peak value and hence the return period is similar after a certain length.

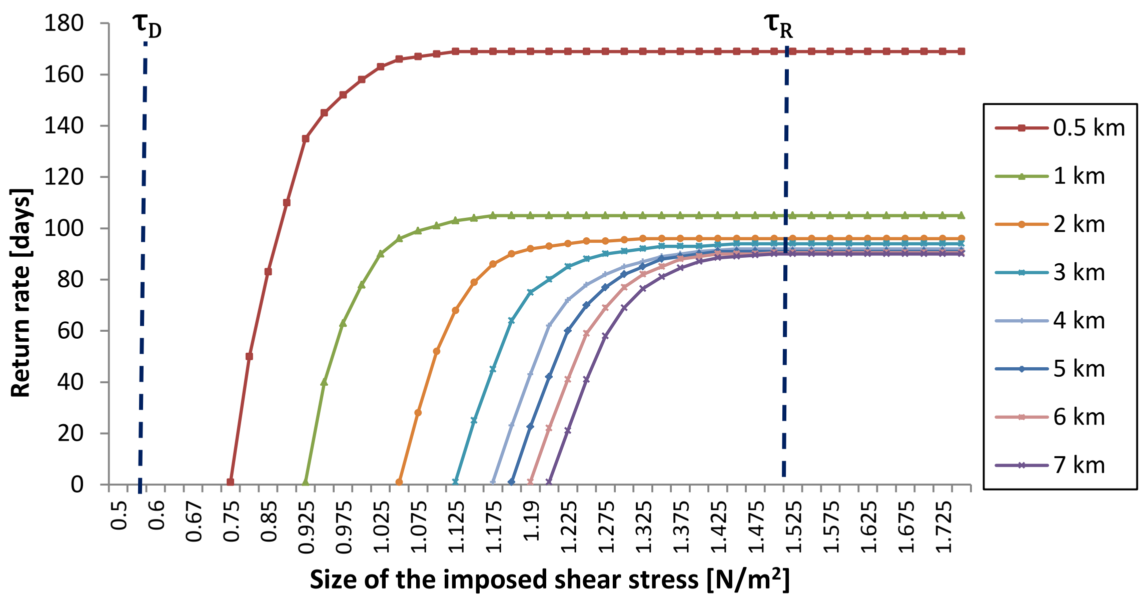

Figure 57: Sensitivity analysis of trade-off curve for varying pipe lengths for a given resilience τ_R = 1.5 N/m^2. Idealised model conditions (Figure 53) length set at L = 1.0 km

Figure 58 presents the diameter effect on the trade-off curve where the imposed shear stress had little influence on return period for the largest diameter pipe. However, the return period was quicker with the reduction of diameter sizes and hence more influential for smaller diameter pipes. From Figure 58 it can be observed that the return period has little impact on relatively larger diameter pipe systems within the modelled network configuration. This is due to the dilution effect of material being mobilised into the bulk water as the model treated turbidity as concentration. Since the shear stress was maintained constant as irrespective of diameter for sensitivity assessment, the flow rate was much higher in larger diameter pipes compared to smaller ones. As a result in the scenarios investigated here when a τ_R event was applied, the 200 mm pipe diameter has two times higher surface area to volume ratio than the 500 mm pipe (Figure 58). Hence the smaller the pipe diameter, the less dilution of wall mobilised material in the bulk flow and the higher the resulting observed turbidity and increased return frequency required to manage this.

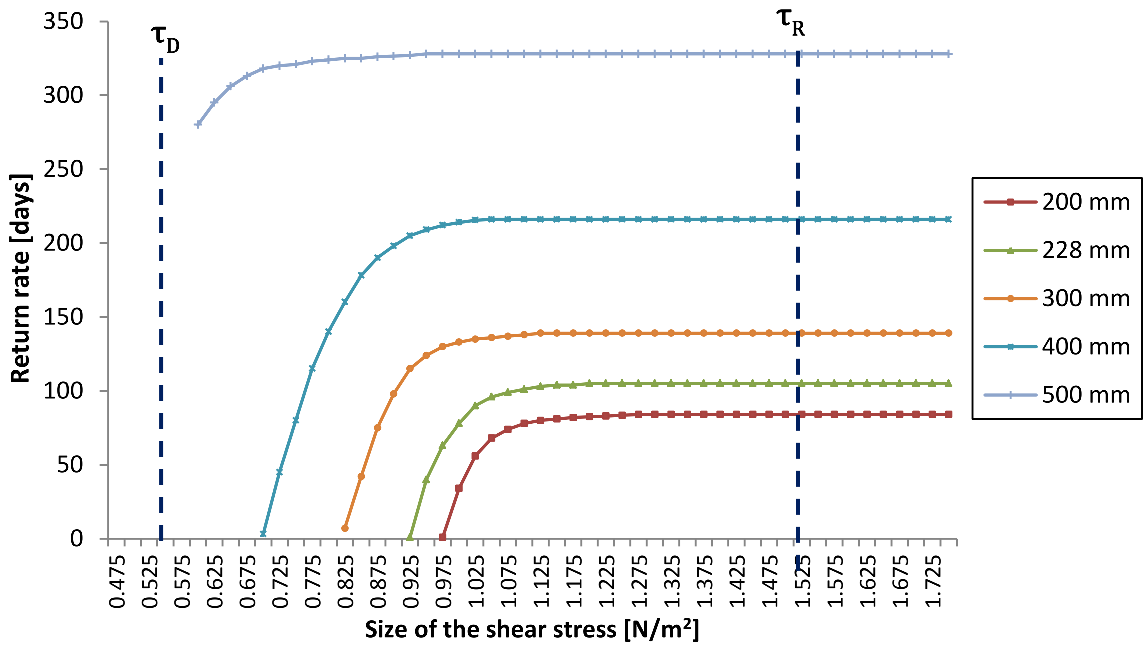

Figure 58: Sensitivity analysis of trade-off curve for varying pipe diameter for a given resilience τ_R = 1.5 N/m^2. Idealised model conditions (Figure 53) set at D=228 mm

8.6.4.2 Accumulation rate

Figure 59 presents the effect of accumulation rate on the trade-off curve showing a linear increase with the increase of accumulation rates. The minimum shear stress required to have return frequency of one day was same (= 0.925 N/m^2) for all accumulation rates. This is due to network accumulating enough material irrespective of accumulation rates to generate maximum one day return period. Although Figure 59 scaled linearly after 1.125 N/m^2 imposed event, initial slopes were different for varying accumulation rate (β_r).

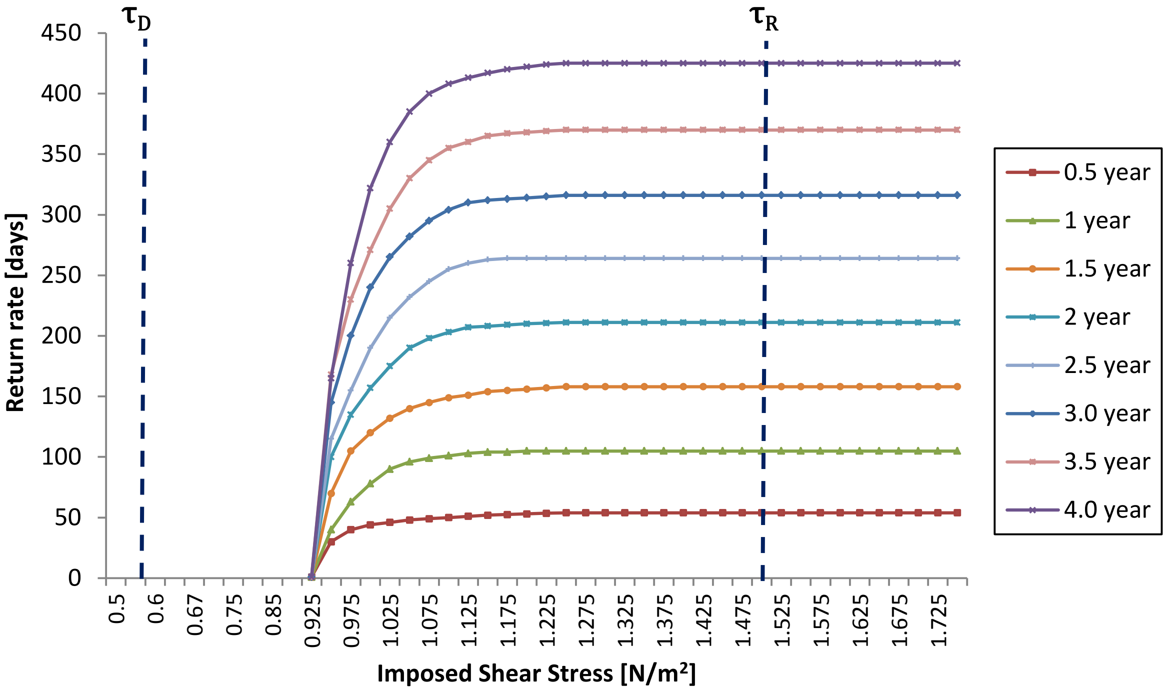

Figure 59: Sensitivity analysis of accumulation rate on imposed shear stress and return frequency for resilience τ_R = 1.5 N/m^2. Idealised model conditions (Figure 53) set at β_r=1.0 year

Since the accumulation rate (β_r) has a direct influence on intervention return rate, further assessment was undertaken to evaluate β_r on cost against resilience. Figure 60 presents the higher the βr (the slower material accumulates), the lower the five-year intervention costs. Although the cost for varying βr was similar in the lower hydraulic resilience region, the exponential relationship increases cost differences at higher resilience.

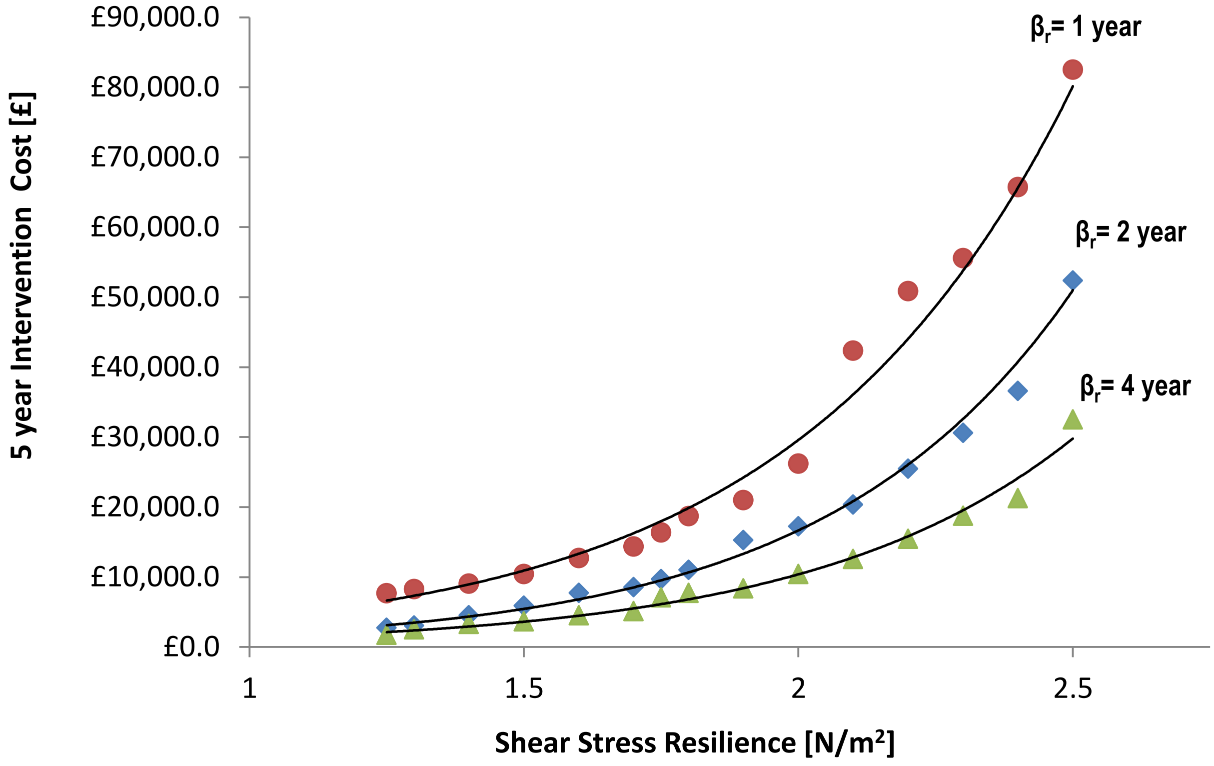

Figure 60: Accumulation rate effect on five-year intervention costs against resilience

8.7 Discussion

8.7.1 Trade-off diagram and cost assessment for fixed resilience

A novel methodology is presented in this paper for designing flow conditioning cycles in a demand driven network by considering long-term OPEX against hydraulic resilience. While previous models determined TOTEX based on structural performance and water quantity, this is the first attempt to model discolouration risk as a water quality performance where only OPEX is required to manage the discolouration risk using flow conditioning intervention.

The proposed WLC model developed a non-linear relationship between imposed shear stress magnitude and return frequency indicating that complex non-linear material layer conditions exist on the pipe wall. Cost profile for shear stress and its return frequency had a low point and linearly increased afterwards with some steps (Figure 54). This cost profile was anticipated as costs are dominated by repeat trials where lower shear stress interventions require a higher frequency. The steps are linked to increased water discharge and resource time when multiple flushing steps are required to achieve the desired resilience within the 1.0 NTU intervention constraints. The applied shear stress magnitude and frequency trade-off results demonstrate that varying magnitude interventions can provide the same protection against discolouration risk; however, cost can vary with the magnitude of intervention. The selection of flow conditioning magnitude has substantial impact on the intervention cost, as shown in Figure 54, suggesting a necessity of a trade-off between shear stress magnitudes and return period and associated intervention cost.

8.7.2 Flow conditioning in non-demand driven network

Implementation of flow conditioning in a demand driven network is relatively complex compared to the non-demand driven network described in the methodology section (Chapter 8.4.1). While no survey has indicated what percentage of the network comes within this category, it is plausible to assume demand-driven mains could cover up to 50% of the total network where populations are uniformly distributed in a relatively small land areas, e.g. Europe. This indicates the necessity of designing specific interventions for demand driven systems.

A significant part of the cost assessment involves disposal of the water used for a demand driven network. While this is not ideal from an environmental viewpoint, on-site manual control of flow conditioning discharge is required when flow is demand driven to avoid any discolouration risk failure. Water discharge during interventions can be avoided if networks have an appropriate infrastructure and constant periodic daily flow profiles, such as typically used to fill downstream reservoirs. Intervention in these cases can be facilitated by increasing the shear stress to a target level via appropriate valve operation managing flows between parallel pipes (Cook et al., 2015), valve operations in looped networks controlling flow direction and magnitude and/or reservoir fill rates via valve or pump control. The processes can be fully automated by a Programmable Logic Controller (PLC) with minimal or zero resource cost and no water wastage (Cook and Husband, 2017). However, automation processes and equipment costs requiring potential CAPEX investment are variable between utilities. As a result this aspect has not been included within the scope of this work.

8.7.3 Pareto front assessment

The modelling framework of Pareto front assessment demonstrated that cost profiles had an exponential relationship to hydraulic resilience (Figure 56). This is due to the higher frequency of interventions required to sustain higher resilience. Additionally, to maintain higher resilience, higher magnitude interventions are required which impact the resource costs, with increased multiple shear stress steps necessary to satisfy the 1.0 NTU operational constraints. While the appropriate choice of pre-selected hydraulic resilience (τ_R) is often unknown, this non-linear representation does however give the users a unique opportunity to determine the best-suited flow conditioning program based on the desired hydraulic resilience and budget available for discolouration management. Thus the proposed modelling framework is the first model that can be used as a decision support tool with a proactive informing discolouration risk based management approach. The exponential correlation of cost against hydraulic resilience is potentially transferable for a similar type of network and accumulation rates. This transferability could be a valuable tool for developing initial budgets for discolouration management before upcoming fiscal periods, e.g. UK water industry Asset Management Period 7 (2020-2025) cycle.

It is however necessary to generate as many possible solutions within the Pareto front range as possible so that the Pareto optimal band can be used by the decision makers to inform risk proactively. While work undertaken here used batch simulations based on an idealised network system, the process can be automated to produce optimum costings for a given resilience within any network and design constraints.

8.7.4 Sensitivity analysis: Accumulation rates, length and diameter

In this work, five-year cost profile was dominated by intervention return frequency (Figure 55), which was primarily dictated by accumulation rates. The methodology effectively demonstrates the improvement of five year OPEX with the improvement of accumulation rates (Figure 60). While improving treated water quality can improve accumulation rates (Vreeburg et al., 2008), it can be expensive, e.g. manganese removal (Postawa et al., 2013). This study maps a Pareto front to assess the trade-off between cleaning intervention with treatment works CAPEX investment and how OPEX is justifiable against CAPEX investment over asset life span (Figure 60). While previous works showed that both flow conditioning intervention (chapter 4) and treated water quality

(Vreeburg et al., 2008) can improve downstream network discolouration risk, this work demonstrates that a potential trade-off solution between water treatement upgradation and trunk main intervention can inform risk in a more robust manner. This is the first proposed WLC model that accounts for the cleaning intervention and WTW improvement processes to manage discolouration risk and can be used as a decision support model. With this proposed model the operator can find the synergy between tuning of WTW upgrade works and network maintenace cost such that the risk can be optmised from WTW to downstream on a network approach basis.

The sensitivity result suggests that the selection of trunk main length has non-trivial impact on managing discoloriation risk via flow conditioning. Since long trunk mains require potentially long pipe turnovers and discharge volumes, suitable conditioning lengths can be determined from sensitivity analysis by assessing the trade-off curve, hence reducing the overall cost of flow conditioning programs. While selection of length for flow conditioning can influence operation decisions, diameter has a different influence on the trade-off curve. The smaller the pipe diameter, the lower the dilution of wall mobilised material in the bulk flow and the higher the resulting observed turbidity and increased return frequency required to manage this. Although the larger diameter pipes carry much higher volumes of water, these typically do not supply directly to downstream distribution zones. Diameter is therefore a significant part of this methodology that considers the impact on demand-driven system intervention cycles. Overall both length and diameter assessment suggests that these have an influence on fixed resilience curve and require site-specific simulations to explore their impact on the operation decisions.

8.7.5 Improving hydraulic resilience for a new and invasively cleaned pipe

While the methodology of this paper focusses on flow conditioning for ongoing OPEX determination against hydraulic resilience, it can be extended to investigate different intervention strategies, e.g. flow conditioning in a new pipe or following an invasive cleaning intervention. A schematic diagram is presented in Figure 61 demonstrating how periodic flow conditioning can manage discolouration risk and hydraulic resilience safely in a new pipe (or fully clean) system. The proposed methodology to design flow conditioning in a new or fully clean pipe can be facilitated in the VCD model by setting initial wall layer condition at φ=0.0, which means no material is present on the pipe wall (Furnass et al., 2014). While this methodology is designed for the new or fully clean pipe, the initial material condition ($\varphi(\tau,t)$) is uncertain after invasive cleaning application and hence setting φ=0.0 will not be applicable for invasive cleaning intervention. The value of invasive cleaning can be evaluated from its capacity to remove legacy deposits from the pipe wall that may contain substances of more concern and what is entering systems according to current WTW standards. However, no previous study has investigated material layer conditions after an invasive cleaning intervention and hence setting $\varphi(\tau,t)$ for design could provide uncertain results. Therefore, to assess $\varphi(\tau,t)$ for an invasively cleaned main, long-term continuous flow and turbidity data are necessary for both pre and post intervention so that the VCD model can track any material conditions changes caused by the invasive cleaning system.

Figure 61(a) shows material conditions in a new and normal operational pipe at t=0, and after a period of material accumulation at all shear strengths simultaneously, for a new pipe at t+ Δt(1) period. The imposed flow conditioning mobilises target strength material (τ_c) at t+ Δt(2) from both normal operating main and new pipe wall, shown in Figure 61(a). However, over time (t+Δt(n)) material accumulates irrespective of preceding material legacy or intervention type and reaches a level similar to a network operating for a sufficient time with layer equilibrium with daily applied shear (τ_D). This consistent material accumulation is a critical conceptual result of this work, indicating that to safeguard against a target resilience, flow conditioning is as effective as any other intervention technique or even new pipe. The constant accumulation conditions also highlight that once in operation a fully clean pipe cannot exist, and any maintenance is only temporary. Figure 61(b) shows how network resilience in new pipe systems can be increased by applying periodic flow conditioning interventions with safe downstream turbidity response ($\leq$1.0 NTU). The low turbidity response during trials in a cleaned pipe is anticipated as following rehabilitation reduced material will present on the pipe wall. In this manner, however, even with a maximum burst event, the network can be guarded over its lifespan, such that there is not enough material to create a threshold discolouration response.

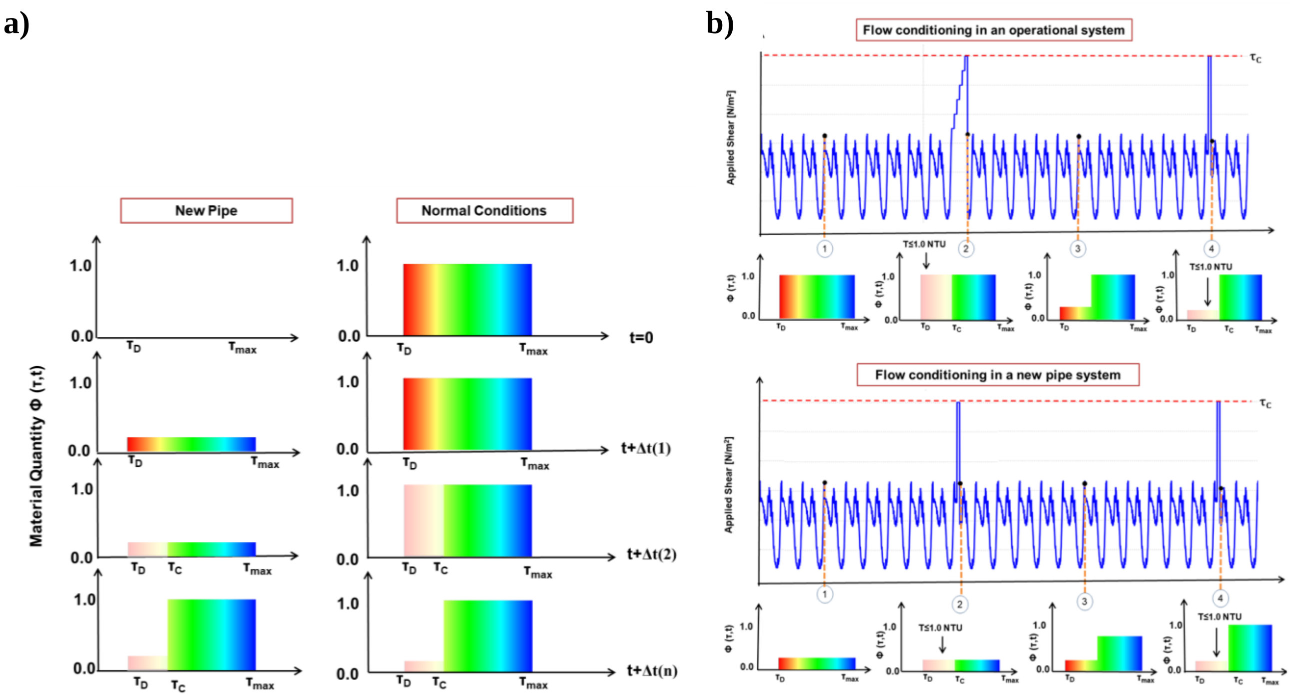

Figure 61: Managing discolouration risk for a new (or fully clean) pipe using combined interventions a) comparison of material accumulation behaviour over time in a new pipe (left column) and pipe in operation for sufficient time for layers to be at equilibirum with daily flows following flow conditioning intervention ($\tau_{C,}$ right column), b) Managing hydraulic resilience via periodic flow conditioning with safe turbidity mobilisation (≤1.0 NTU) in normal operating conditions (top plot) and in a new pipe conditions (bottom plot).

Typically the charge for cleaning intervention service is financially constrained, such as by regulators in the UK through customer price caps (Engelhardt et al., 2002). Several studies raised concern about this price cap due to water utilities potentially needing to invest impractical amounts in the future to manage infrastructure and water quality. For example, a report produced by AWWA (2012) stated that about $1 trillion in funding would be required over the coming 25 years to manage and deliver clean water effectively considering both aged asset rehabilitation and meeting the demand of growing populations. While the cost of cleaning intervention is huge, to manage this type of extreme investment water industry requires cheaper intervention. This study shows flow conditioning is a relatively cheaper alternative compared to the other known maintenance strategies as it only uses system hydraulics to manage discolouration risk and no specialist tools are required for operation. Unlike other rehabilitation techniques, flow conditioning requires only OPEX, and it can be implemented in a range of network conditions, e.g. in normal operation, new pipes or after invasive cleaning conditions (Figure 61). While a one-off flow conditioning intervention may be cheaper to implement, the Pareto front solution (Figure 56) shows that cost of flow conditioning can increase exponentially with increase of desired hydraulic resilience. In order to tackle this type of extreme investment the operator requires a decision support model, e.g. the proposed WLC model. The exponential Pareto solution is a good example of how the operator can use this type of model to take decisions based on operational constraints and available budget and manage risk for the end users.

It is possible that a combined application of flow conditioning with another rehabilitation strategy can provide sufficient hydraulic resilience with reduced cost. While the proposed methodology in this paper is based on OPEX assessment (Figure 51), with the updated method as shown in Figure 61, CAPEX investment for installing new pipes or relining old CI main against long-term OPEX of flow conditioning can be compared, and overall TOTEX can be minimised. Although the trade-off between CAPEX and OPEX comparison (Figure 61) is not demonstrated in this paper, future work can be used to investigate these options with supporting field data to help develop holistic discolouration management strategies incorporating different intervention types.

8.8 Conclusions

This paper presents a novel methodology for designing cost-effective trunk main flow conditioning intervention cycles trading OPEX against hydraulic resilience using validated discolouration process understanding and modelling.

- The work demonstrates the use of VCD model to develop a trade-off diagram between applied shear stress and discolouration risk-return frequency for a fixed hydraulic resilience. By predicting the risk-return period for any imposed intervention for a pre-defined hydraulic resilience, network operators can choose the magnitude of the intervention and return period based on the network suitability and operational constraints.

- The relationship established between varying imposed shear stress conditions and the operational costs facilitates determining the lowest operating cost for a given resilience scenario.

- The Pareto front methodology can be used to identify a suitable flow conditioning cycle comparing cost and hydraulic resilience. This novel methodology can be used as a decision support model where an operator has budget constraints and can choose a different level of network resilience depending on investment availability and network conditions.

- The accumulation rate show non-trivial influence on shear stress and its return period trade-off curve for both fixed resilience and Pareto front curve. The Pareto set solutions provides an unique opportunity to inform managing discolouration risk from WTW to downstream network approach by trading between costs of network maintenance and upgrading treatment works.

- Both length and diameter trade-off curve for the fixed hydraulic resilience shows that these are site-specific and simulation required for each pipe system to inform risk proactively.

9. Combined Discussions and Future Works

Fundamentally this research work explored how controlled interventions can be applied to distribution networks to manage long-term discolouration risk. The work focussed on flow conditioning as a key strategy and compared the outcomes to network with no interventions. Extensive fieldwork, data monitoring and discolouration modelling were undertaken to evidence the findings. In order to assess the flow conditioning concept as a long-term strategy, multiple methodologies (Chapter 4,5,6,7 and 8) were developed in relation to scientific knowledge gathered from previous work and new ideas were developed aligned to rational justification. Attainment of the aims and objectives set out at chapter 3 are reported through four independent journal papers and a published conference paper. The first three chapters assess selected cleaning interventions long-term impact on water quality from part of a water distribution network, the fourth chapter explores the ability of the VCD model for simulating long-term discolouration behaviour and the final chapter models cost-effective discolouration management strategies comparing cost against hydraulic resilience. While each chapter answers a specific objective (chapter 3.1) that coherently justifies the overall aims of the thesis, additional knowledge regarding discolouration processes, modelling functionality and intervention efficiency has been further explored from the five chapters.

9.1 Discolouration processes

In this work, several flow conditioning intervention and flushing field trials demonstrated that each step increase of shear stress mobilises additional material. This occurs both from small diameter and large diameter pipe walls confirming discolouration material cohesive strength properties (Figure 12 & 18). No sedimentation effect was observed from trunk main low points (Figure 32b) during flow conditioning trials where flow was in fully turbulent ($Re=10^4$) conditions (chapter 6). Pipe cut-out prior to invasive interventions from the same pipe low point showed that material accumulates ubiquitously on the pipe wall and no invert deposits were observed (Figure 29). The gathered information about discolouration processes is supported by several previous studies that discolouration material exhibit cohesive strength properties with weaker layers on top of stronger ones (Boxall et al., 2003b; Boxall and Saul, 2005; Husband and Boxall, 2010, 2011). The findings from this thesis contradict some previous studies that state sedimentation effects causing discolouration material deposition (Vreeburg, 2007; van Thienen et al., 2011) and discolouration modelling based on gravitational effects, e.g. particle sedimentation model (Ryan et al., 2008).

9.2 Accumulation processes

Periodic flow conditioning and burst events in multiple trunk mains and flushing in multiple DMAs demonstrated that material accumulates on pipe wall at varying strengths simultaneously (Figure 12 and 18). While the previous work observed this accumulation behaviour in small diameter pipe (Husband and Boxall, 2011; Husband et al., 2010; Sharpe, 2012), this work highlighted the same behaviour for large diameter pipes (Figure 12). This accumulation process was further tested via the VCD model where model functionality allows accumulating material at all strength simultaneously (chapter 7). VCD model simulation performance to measured turbidity responses confirms accumulation behaviour occurs across the range of cohesive layer strength simultaneously. The significance of understanding and modelling this accumulation behaviour facilitates managing varying strength material layers effectively and minimising discolouration risk proactively via flow conditioning interventions.

9.3 Accumulation rate or return period

Accumulation return period through VCD model calibration was found between 1.65-1.85 years for the three trunk mains (chapter 7.6.3). DMA pipe accumulation return interval, supplied from the same trunk mains, was estimated between 1.5-3.7 years (table 4). Although the accumulation rate result of large diameter mains (trunk main) and small diameter pipes (DMA) are relatively different, they are also not directly comparable. Trunk main accumulation rates was estimated through the VCD modelling technique with a defined methodology (chapter 7.5). However, no continuous measured data was available for the selected DMAs pipes to calibrate it via VCD modelling. Hence accumulation rates at DMA level were estimated by mass flux analysis induced from repeated flushing (chapter 4.6). Also, pipe material, diameter and hydraulics are different between the trunk main and DMA studied pipes (table 1 and 4). This combined effect can impact on the accumulation rates (Cook and Boxall, 2011; Husband and Boxall, 2011; Pothof and Blokker, 2012; Sharpe, 2012) and help explain the difference between the results from large and small diameter pipes. Although accumulation return period have been estimated by repeated flushing in several studies (Blokker and Schaap, 2015a; Husband and Boxall, 2011), results can be limited by not capturing the effect of recent and unusual hydraulic behaviour, e.g. bursts. Hence it is proposed estimation of accumulation rates by the VCD model can provide higher confidence as demonstrated by the long term simultaneous tracking of both mobilisation and accumulation processes.

9.4 Bulk water effect on accumulation rate

Long-term monitoring and repeated flushing results show that accumulation return period at the downstream network increased with higher background turbidity loading (table 4). The material accumulation rate was found similar for pre invasive and following flow conditioning trials suggesting risk return on pipe wall at a similar rate influenced dominantly by bulk water. This suggests that the accumulation rate is a function of bulk water quality which agrees with previous studies (Blokker and Schaap, 2015a; Cook and Boxall, 2011; Husband and Boxall, 2011; Vreeburg et al., 2008). The VCD model calibration also supported this as accumulation rates were found transferable for similar water quality (chapter 7). While improving treated water quality can improve accumulation rate (Vreeburg et al., 2008), this study shows that applying periodic flow conditioning intervention can have a similar chronic effect by reducing the background loading. Thereby a novel trade-off between treated water quality and cleaning interventions was developed by trading CAPEX of treatment works improvement with ongoing trunk main maintenance OPEX in the chapter 8 (Figure 60).

9.5 Temperature effect on discolouration process

Mass balances analysis induced from periodic flow conditioning trial showed that temperature potentially has an influence on discolouration risk (Figure33, chapter 6). A different approach was undertaken by calibrating the accumulation rate (β_r) of VCD model to one trunk main (TM-1) quarterly measured data. Similar to mass-balance analysis, modelling results was also found temperature influence on accumulation rates and hence discolouration risk. The correlation between temperature with chlorine residual (Figure 25, chapter 5) and total organic carbon (Figure 37a, chapter 7) was also evident from long-term data monitoring which can potentially contribute to the discolouration risk by increasing microbiological activities during warmer season. These findings agree with the previous works of Blokker and Schaap, 2015b and Sharpe, 2012. However due to the small sample size, this correlation cannot be confirmed from this study alone.

9.6 VCD model functionality

The fieldwork results showed that repeated flow conditioning interventions reduces background turbidity levels by managing wall bound material layers (Figure 17) and a process for this improvement was described in Figure 21. This behaviour suggesting a cyclic material mobilisation and accumulation processes exists and material transport from bulk water to wall has critical impact on chronic turbidity loading. However, VCD model assumes material transport from bulk to wall is negligible compared to the wall to bulk water (Furnass et al., 2014). Although the VCD model is unable to simulate the cyclic material accumulation and mobilisation process as shown in Figure 21, calibration results showed that the difference can be adjusted by tweaking material accumulation rate parameter (β_r). While this material accumulation-mobilisation from bulk to wall processes can be integrated in the VCD model, only with the calibration of β_r model parameter can be produced sufficient simulation accuracy to the long term measured data. Hence it can be stated that the current functionality is sufficient to simulate accurate turbidity output.

9.7 Trunk main cleaning effect on water distribution network

Results show that higher continuous material loading from the trunk main can increase accumulation rates in the downstream network (table 4). This is consistent with previous studies, e.g. (Blokker and Schaap, 2015a; Vreeburg et al., 2008) where bulk water quality is found as the dominant factor for accumulation rates. DMA performance in terms of discolouration PCV failure at customer tap (≥4.0 NTU) was found better from the flow conditioning trunk mains compared to the control main network (Figure 19 and 20). Chlorine decay assessment shows that higher chlorine residual was measured from the flow conditioned main, indicating improved DMA performance against microbial contamination (chapter 5).

While this work investigated the trunk main flow conditioning impact from part of a WTW outlet to tap approach, the impact on customer taps has some uncertainties. Several studies have shown that premise plumbing has a significant impact at tap level drinking water quality and in many cases traces of discolouration material can be present, e.g. iron particles can originate from corroded plumbing material (Jang et al., 2011; Lytle, 2009; Viraraghavan et al., 1996). Since selecting and installing plumbing material of household service connections is not water company's responsibility, it adds uncertainty when evaluating water quality based on customer taps and observed discolouration. This is an area that requires further investigation. Thus it is reasonable to state that cleaning intervention impact should be assessed as part of a WTW outlet up to downstream customer property boundary.

9.8 Comparison of Flow conditioning and other interventions

The primary focus of this study was to test whether flow conditioning is a cost-effective long-term discolouration management strategy compared to no interventions. While flow conditioning can be implemented in the operational network without isolating the main, for invasive cleaning it is not an option. Hence this type of intervention can cause severe customer disruption. In order to test flow conditioning performance, varying magnitude and interval flow conditioning was implemented successfully in multiple trunk main systems (chapter 4 and chapter 6). This research demonstrated that flow conditioning not only improves trunk main long-term turbidity behaviour but also improves material accumulation rates for the downstream network (chapter 4). However, a critical risk was found after the ice slurry pigging intervention (chapter 6). While ice slurry pigging improved the hydraulic capacity of the trunk main, no study has been undertaken that confirms similar for flow conditioning. The WLC modelling framework using the validated VCD model also demonstrates that flow conditioning is a relatively cheaper alternative compared to other rehabilitation programs (chapter 8.7.3).

Apart from its cleaning performance, flow conditioning can also be effectively used to assess discolouration risk performance for a new or invasively cleaned pipe (chapter 6). Long-term hydraulic and water quality (chlorine) monitoring with chlorine decay modelling (Rossman, 2000) also showed that chlorine wall decay improved following imposed events and there is a relationship between shear stress magnitude and chlorine wall decay (chapter 5). While the calibration was undertaken only for the wall decay parameter by keeping bulk decay constant for the whole simulation period, the reduction of trunk main chronic loading suggests that bulk decay will also reduce over time due to the periodic flow conditioning. However, due to the seasonal bulk decay data unavailability, this complex process needs further investigation.

9.9 Proposed future works

In order to evaluate the concept that flow conditioning is a long-term cost-effective discolouration management strategy, a broad range of aims and objectives were developed and tested in operational networks and validated via modelling analysis. Following the discussions, there are several opportunities to extend the current work to address further knowledge gaps:

1. Comparison of long-term water quantity and quality benefits of invasive cleaning with other known interventions, e.g. flow conditioning. The developed methodology in this thesis could be used to explore this type investigation.

2. Design of invasive cleaning interventions cost profile compared to flow conditioning intervention using the VCD model material tracking functionality. This can eventually demonstrate if flow conditioning or invasive cleaning interventions are the most cost-effective long-term discolouration management solutions.

3. Explore the trade-off between WTW upgradation e.g. Mn removal and different trunk main cleaning interventions for managing long-term discolouration risk. It will be interesting to explore if tuning treated water or imposing cleaning intervention provides better long-term discolouration management options in terms of water quality and cost.

4. Implementation of proposed WLC modelling framework into commercial drinking water modelling software for wider application.

10. Conclusions

This research work explored for the first time the long-term impact of controlled interventions on discolouration risk as part of a WTW outlet to downstream network approach. A particular feature was consideration of how such interventions can be best applied when considering operational expenditure against the level of hydraulic resilience achieved. Central to the thesis is the concept of in-service flow conditioning as a cost-effective long-term discolouration management strategy. This research enlightens for the first time how our trunk main and downstream network discolouration risk behaves due to the periodically controlled interventions and how risk can be managed proactively.

The field experimental investigations observed for the first time the long-term impact of trunk main flow conditioning intervention on selected water quality. An improvement of long-term background turbidity or chronic material loading was identified for each trunk main. Assessing of downstream material accumulation rates for the test trunk mains fed network demonstrated that chronic loading is significantly more influential on discolouration risk than immediate alleviated acute loading from flow conditioning trial. This suggests flow conditioning intervention not only lowers long-term discolouration risk for trunk mains but also for the connected downstream network showing its capabilities to manage discolouration risk from part of a treatment outlet to downstream network approach. Chlorine wall decay was also improved due to the periodic flow conditioning intervention and found an inverse relationship between imposed shear stress and wall decay coefficients. Since flow conditioning reduced trunk main chronic loading, it is conceptualised that this lowered the chlorine bulk decay as well suggesting it’s dynamic water quality benefits. However, due to the limited bulk decay samples, this thesis cannot confirm this water quality improvement behaviour. While long-term water quality benefits of flow conditioning intervention were observed, an invasive cleaning termed “ice slurry pigging” performance was not found adequate against managing discolouration risk, due to loose particles remaining on the trunk main after the intervention and posing further discolouration risk. Improvement in hydraulic pipe roughness was found following the ice slurry pigging intervention; however, the higher measurements observed after 12 months of trial suggest that continuous material fouling potentially impacts on pipe roughness as well. The evidence from robust fieldwork shows that risk remains and returns on the pipe wall after a while, even after an expensive intervention, and hence regular cleaning maintenance is required to manage risk.

This work found accumulation occurs continuously and at all strengths simultaneously for both large and small diameter pipe systems adding more knowledge to the material accumulation processes. This varying strength accumulation process was encapsulated by the VCD model which was tested for simulating long-term turbidity behaviour. A novel methodology was developed to validate the VCD modelling functionality and model simulated long-term discolouration behaviour successfully with high accuracy. From the repeated field study and by simulating the measured data in the VCD model it was confirmed that the processes of material mobilisation and accumulation occur continually and accumulation occurs at all strengths simultaneously. This improved understanding agrees with the previously explored knowledge and concept. This is the first model that provides robust validation of accumulation functionality and simulates both mobilisation and accumulation continually.

Derivation of this complex knowledge both via fieldwork and modelling allowed the opportunity to develop a cost-effective trunk main discolouration management strategy. A novel methodology was developed using the validated VCD model to design cost-effective flow conditioning cycle trading against hydraulic resilience. The validated VCD model material tracking functionality allows the user for the first time to design flow conditioning long-term intervention pro-actively in such a way that it can guard the network against any hydraulic event discolouration risk. While picking pre-selected hydraulic resilience for a network is often unknown or difficult, an exponential relationship drawn from Pareto front solutions of intervention cost against hydraulic resilience provides the operator with a unique prospect of deciding the best-suited intervention considering budget constraint. The WLC model effectively shows that it can be used as a decision support model. The significance of this study has been extended by conducting a comparison of flow conditioning with other interventions and showing that it is cheaper to implement than other known interventions, suggesting its viability for use as a long-term discolouration management strategy.

From the fieldwork experimental study it is also evident that not only can discolouration risk be prolonged via bulk water improvement but also a synergy exists to manage risk between treated water improvement and trunk main cleaning interventions. A trade-off curve between CAPEX of treatment upgradation and OPEX of flow conditioning against hydraulic resilience was developed. This novel trade-off demonstrates the WTW upgradation effect on material accumulation rate could readily be included into the model and trade of the cost-benefit analysis from WTW to downstream network discolouration management approach.

Overall, this thesis has described the flow conditioning long-term impact on selected water quality, observed the accumulation process in the large diameter pipe and provided confirmation via simulation in the VCD model. This innovative understanding of discolouration processes was further transferred into a modelling framework to develop a novel model trading cost against hydraulic resilience. Each chapter uses enhanced scientific methods and provides a solution to a specific objective that has led this thesis as a whole to conclusively provide a holistic discolouration management strategy from WTW to downstream network. Table 15 summarises the output of each paper and its significance.

***Table 15**: Conclusions of each chapter and their significance*

Output	Significance
Chapter 4: How Chronic and Acute Material Loading Impacts Discolouration Risk in a Water Distribution Network	
Chronic material loading from bulk water is more significant than acute loading from flow conditioning interventions in terms of downstream network accumulation rate and hence discolouration risk	Occasional acute loading from flow conditioning intervention does not increase discolouration risk and improving bulk water quality can improve discolouration risk
Periodic flow conditioning intervention improves bulk water chronic material loading	Benefits of flow conditioning for trunk mains discolouraiton risk
Accumulation rate in downstream network is reduced with repeated flow conditioning.	No negative effect observe from flow conditioning acute loading to DMA's discolouration risk
Adding further evidence of material accumulates processes that it returns at all strength simultaneously on both large and small diameter pipes	Long-term and universal nature of material accumulation process in drinking water network .
Chapter 5: Discolouration Risk and Chlorine Wall Decay	
Periodic imposed excess shear stress events reduces chlorine wall decay	Benefits of flow conditioning intervention to limit chlorine wall decay
The higher the applied shear stress, the better the observed chlorine wall decay benefit.	Design of appropriate imposed shear stress

The improvement of chlorine wall decay was found to be temporary	Require regular hydraulic interventions requires to maintain the benefit
Chapter 6: Quantity and Quality Benefits of an In-service Invasive Cleaning of Trunk Mains	
Roughness reduces 7 times, however, roughness increases slowly after 12 months	Quantity benefits of the invasive cleaning intervention, however, one-off intervention is not enough to maintain the benefit
Significant turbidity response after ice slurry pigging intervention	Loose particle remain on pipe wall and hence discolouration risk pertains even after expensive cleaning process
Amount of mobilised material correlate with treated water temperature	Microbial role in discolouration material accumulation process.
Chapter 7: Simulating Long-Term Discolouration Risk Behaviour in Large Diameter Trunk Main	
Model can track long-term material mobilisation and accumulation with an accuracy of ±0.25 NTU	User can assess risk for any event in any given time period with high precision including simulating flow conditioning trial
Accurate turbidity simulation result validates the concept of material mobilisation-accumulation processes occurring continuously, and accumulation occurring at varying shear strength simultaneously on the pipe wall.	Use VCD model functionality to inform discolouration risk proactively and potentially develop whole life costing model
The similar accumulation rate under varying hydraulic conditions	Bulk water has greater impact on accumulation processes.
Accumulation rate is a function of process dependent conditions rather than material supply rate dependent processes.	Cleaning interventions are effective only as a removal of amount of material and if there is no periodic intervention undertaken, discolouration risk returns to similar conditions after certain period
Chapter 8: Strategic Planning to Manage Transmission Main Long-term Discolouration Risk	
A novel methodology was developed to design flow	The VCD model capabilities to design whole life

conditioning cycle against hydraulic resilience incorporating discolouration processes	costing model
Trade-off diagram between varying imposed shear stress and cost determining the lowest operating cost for a fixed resilience	Operator can choose the best possible magnitude and return frequency of flow conditioning for a given network conditions.
Proposed methodology can be used to identify a suitable flow conditioning cycle comparing cost and for any hydraulic resilience	Flexibility of designing flow conditioning cycle considering budget constraints and using it as decision support tool.
The accumulation rate and network hydraulic characteristics (length and diameter) show non-trivial influence on shear stress and its return period trade-off curve	Accumulation rate can be used to assess CAPEX of treatment improvement and OPEX of flow conditioning. Length can inform operational decision and diameter can help to take intervention feasibility decision.
Potential extension of proposed methodology to design WTW improvement and new or invasive cleaning system process	Comparing cost of WTW upgradation with different interventions and minimising TOTEX of cleaning strategy by managing risk from WTW to downstream networks.

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